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EVALUATION OF A NEW MOISTURE MEASURING METHOD FOR DETERMINING ON-LINE MOISTURE CONTENT IN BIOMASS FEEDSTOCK

RENEWABLE ENERGY DIVISION

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PREFACE

A new method was recently developed at Forintek Canada Corp.'s Western Laboratory, for measuring moisture content (m.c.) in unseasoned veneer and lumber. The method is based on applying a known quantity of heat energy to a wood surface and measuring the temperature rise. The temperature rise was found to be correlated with m.c. The method showed promise for measuring m.c. in other unseasoned wood materials. The purpose of this project was to construct and evaluate a new moisture sensor based on a preheating principle to measure m.c. in hog fuel materials.

The results in this report showed that the new moisture sensor, incorporating infrared point heat sensors, performed well in measuring m.c. in hog fuel materials. The new moisture sensor also performed well in measuring m.c. in frozen hog fuel materials.

The development of a moisture sensor to accurately measure m.c. in unseasoned wood materials is significant, since present moisture sensors, using principles such as microwaves, are limited in accuracy. The accurate on-line measurement of hog fuel m.c. is extremely important for the efficient operation of a hog fuel boiler. Poor control of the boiler leads to inefficient combustion and unacceptable smoke emission.

The results in this report will be of interest to hog fuel operators and managers of forest products and pulp and paper companies involved in burning hog fuel.

ABSTRACT

A new type of moisture sensor was constructed and evaluated for measuring on-line m.c. in hog fuel materials. The principle of the new moisture sensor is based on a relationship between m.c. and surface temperature rise after the sample material has received a known quantity of heat energy. Hog fuel materials, ranging from hemlock bark to sieved cedar sawdust, were collected from forest products mills in the Vancouver area and were brought back to Forintek's Western Laboratory for testing. These hog fuel samples were then analyzed for m.c. using the new moisture sensor and a conveyor line system run at 50 ft./min.

Using the new moisture sensor, very good correlations between actual m.c. and temperature rise were found for hog fuel materials under several experimental conditions. The new moisture sensor also showed good promise in measuring m.c. in frozen hog fuel materials.

The accurate on-line measurement of hog fuel m.c. is extremely important for the efficient operation of a hog fuel boiler. The hog fuel is generally fed to the boiler by a conveyor belt system, thus the m.c. must be measured rapidly to permit appropriate furnace adjustments. Changes in hog fuel m.c. are compensated by the use of supplementary fossil fuels. Poor control of the boiler leads to inefficient combustion and unacceptable smoke emission.

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EXECUTIVE SUMMARY

The prime objectives in the present study were to construct and evaluate a new moisture sensor for measuring on-line m.c. in hog fuel materials. The principle of the new moisture sensor is based on a relationship between m.c. and surface temperature rise after the sample material has received a known quantity of heat energy. The accurate on-line measurement of hog fuel m.c. is extremely important for the efficient operation of a hog fuel boiler. The hog fuel is generally fed to the boiler by a conveyor belt system, thus the m.c. must be measured rapidly to permit appropriate furnace adjustments. Changes in the hog fuel m.c. are compensated by the use of supplementary fossil fuels. Poor control of the boiler leads to inefficient combustion and unacceptable smoke emission.

Various methods, including electrical, microwave and nuclear radiation, have been used to measure m.c. in unseasoned wood materials. However, in general these methods are limited in accuracy since they require a knowledge of the bulk density of the material.

A moisture sensor system was constructed at the Western Laboratory, Forintek Canada Corp. The system contained two infrared heaters to preheat the hog fuel samples and three infrared heat sensors to measure temperature rise. The system was interfaced to an IBM-PC microcomputer which collected and analyzed the temperature data.

Hog fuel materials, ranging from hemlock bark to sieved cedar sawdust, were collected from forest products mills in the Vancouver area and brought back to Forintek's Western Laboratory for testing. The hog fuel samples were then analyzed for m.c. using the new moisture sensor. Both non-frozen and frozen hog fuel samples were run on a conveyor system at 50 ft./min.; at depths ranging from one to six inches beneath the moisture sensor. After each run samples were immediately removed and analyzed for m.c. on a green weight basis using the oven dry method. Correlations between actual m.c. and temperature rise, dmean, were determined.

In general, the new moisture sensor showed very good correlation between actual m.c and temperature rise, dmean, for different types of hog fuel material, including cedar sawdust and shavings, sieved cedar sawdust and cedar and hemlock bark. It also showed good correlations between actual m.c. and dmean for aspen pulp chips.

The Telatemp Model 44-2MHE infrared heat sensor gave more accurate m.c. measurements than the Infratrace Model 800 infrared heat sensor. The higher accuracy of the Telatemp could be accounted for by its faster response time to sensing temperature, 0.05 sec., at least twice that of the Infratrace Model.

Overall, better correlations between actual m.c. and temperature rise, dmean, was found for the one inch depth hog fuel materials compared to the three inch depth.

The new moisture sensor performed well for frozen hog fuel materials, as indicated by the good correlations between actual m.c. and temperature rise, dmean. The cooling effect from the heat of fusion of ice caused the temperature rise, dmean, for the frozen hog fuel material to be about two to four degrees lower than the unfrozen material at a given m.c.

The results in this report show there is good potential in measuring m.c. in hog fuel materials using a new moisture sensor incorporating infrared point heat sensors. It is recommended that a commercial prototype moisture sensor using the infrared point sensors be built and evaluated under mill conditions. It has been noted that, whereas the infrared point sensors scan one point only, a high temperature infrared linescanner has recently been developed which can scan temperatures along a line and therefore has the capability of scanning a much larger area than the point sensors. This should allow for even more accurate measurements of the average m.c. in hog fuel materials. It is also recommended that further work be initiated to develop a low temperature infrared linescanner which can be interfaced with the new moisture sensor and evaluated for measuring m.c. in hog fuel materials.

RESUME

Les objectifs principaux de cette étude étaient de construire et d'évaluer un nouveau détecteur d'humidité pour mesurer en continu les teneurs en humidité (t.h.) de résidus de bois. Le principe de fonctionnement est basé sur la relation entre la t.h. et l'augmentation de la température à la surface du matériel ayant reçu une quantité définie d'énergie thermique. La mesure en continu au site de la t.h. de résidus de bois est extrêmement importante pour obtenir un bon rendement des chaudières à combustion. En général, le combustible est alimenté à la chaudière par un convoyeur à courroie. La t.h. doit donc être mesurée rapidement pour permettre des ajustements à la fournaise. Les variation de t.h. sont compensées par une utilisation accrue de combustibles fossiles. De mauvais ajustements à la chaudière amènent une combustion inefficace et des émissions atmosphériques inacceptables.

Diverses méthodes, comprenant par électricité, par ondes courtes et par radiations nucléaires, furent utilisées pour mesurer la t.h. de bois non-séché. Mais, ces méthodes offrent généralement une exactitude limitée car elles nécessitent des mesures de masse volumique du matériel.

Un système de détection d'humidité fut construit au laboratoire de l'ouest de Forintek Canada Corp.. Le système comprend deux radiateurs à infra-rouge pour chauffer des échantillons de résidus de bois et trois détecteurs de chaleur à infra-rouge pour mesurer l'augmentation de température. Le système fut couplé à un micro ordinateur IBM-PC pour collecter et analyser les données de température.

Des résidus de bois, variant d'écorces de pruche à de la sciure de cèdre de l'ouest, furent prélevés d'industries du bois de la région de Vancouver et ramenés au laboratoire de l'ouest de Forintek pour les tests. Les échantillons furent analysés en utilisant le nouveau détecteur d'humidité. Des échantillons gelés et non-gelés furent acheminés sur un système de convoyeurs à 50 pi/min et à des épaisseurs variant de un à six pouces sous le détecteur. Après chaque essai, des échantillons furent prélevés et la t.h. fut mesurée en utilisant la méthode de séchage au four. Des corrélations entre la t.h. actuelle et l'augmentation de température (d moyen) furent déterminées.

En général, le nouveau détecteur d'humidité montra une très bonne corrélation entre la t.h. actuelle et l'augmentation de température (d moyen) et ceci pour différents matériels comprenant de la sciure et des planures de cèdre, de la sciure de cèdre tamisée et de l'écorce de pruche et de cèdre. De bonnes corrélations entre le t.h. actuelle et le d moyen furent aussi obtenues avec des copeaux de peuplier faux-tremble.

RESUME

Le détecteur de chaleur infra-rouge Telatemp Modèle 44-2MHE a fourni des mesures plus exactes de t.h. que le détecteur Infratrace Modèle 800. Cette plus grande exactitude de Telatemp serait attribuable à son temps de réponse à mesurer les températures de .05 secondes, soit au moins deux fois la vitesse du modèle Infratrace.

En général, les résidus de bois sur un pouce d'épaisseur fournissent une meilleure corrélation entre la t.h. actuelle et l'augmentation de température, d moyen, que sur une épaisseur de trois pouces.

Le nouveau détecteur d'humidité fonctionne aussi avec du matériel gelé, tel que démontré par la bonne correlation entre d moyen et la t.h. actuelle. L'effet de refroidissement de la fusion de la glace a produit une hausse de température, d moyen, pour le matériel gelé, de 2 à 4 degrés plus bas que le matériel non-gelé pour une t.h. donnée.

Les résultats de ce rapport démontrent un bon potentiel à mesurer la t.h. de résidus de bois en utilisant un détecteur d'humidité constitué de détecteurs infra-rouges ponctuels. Il est suggéré de construire un prototype à l'échelle commerciale et de l'évaluer sous des conditions réelles en usine. Il fut noté que les détecteurs infra-rouges actuels perçoivent la chaleur à un point spécifique; or un détecteur à haute température pouvant percevoir les températures sur une bande rectiligne a récemment été mis au point et peut donc mesurer une surface beaucoup plus grande. Ceci devrait permettre une mesure encore plus exacte de la t.h. moyenne de matériel biomassique. Il est donc suggéré d'amorcer des travaux de développement pour intégrer ce détecteur infra-rouge à bande dans le dispositif actuel pour mesurer la t.h. des résidus de bois.

1. INTRODUCTION

Hog fuel is used by the forest products industry to describe different forms of wood waste which are used as fuel. Hog fuel can come in the form of sawdust, shavings and wood wastes from sawmills and bark and wood chip rejects (not suitable for pulping) from pulp mills.

The accurate on-line measurement of hog fuel m.c. is extremely important for the efficient operation of a hog fuel boiler. The hog fuel is generally fed to the boiler by a conveyor belt system, thus the m.c. must be measured rapidly to permit appropriate furnace adjustments. Changes in hog fuel m.c. are compensated by the use of supplementary fossil fuels. Poor control of the boiler leads to inefficient combustion and unacceptable smoke emission.

Various methods including electrical (Brady, 1964; Considine, 1974 and Dennis and Beall, 1977), microwave (Balls and Boersma, 1973 and Busker, 1968) and nuclear radiation (Loos, 1965 and Richesson et al., 1967) have been used to measure m.c. in unseasoned wood materials. However, in general these methods are limited since they require a knowledge of the bulk density of the material. In addition, the accuracy is seriously affected by variation in sample temperature and species. In the case of the nuclear radiation method, the equipment is very expensive and personnel must be adequately protected from the radiation source. A method using an infrared reflection technique (Beuther, 1965) has the advantage that it does not require knowledge of the bulk density of the material. However, its accuracy is affected by changes in the material's surface characteristics, such as different species and particle size.

A new method developed at Forintek to measure m.c. in unseasoned wood materials is based on the relationship between surface temperature after heating and m.c. This method was evaluated for measuring m.c. in hog fuel in this work.

2. OBJECTIVE

To build and determine the feasibility of using a new moisture measuring sensor for determining on-line m.c. in hog fuel.

3. EXPERIMENTAL

3.1 Materials

In the first trial, hog fuel was collected from two forest products mills in the Vancouver area, designated A and B. Two locations, 100 yards apart, in the hog fuel pile were selected at each mill and two bags of hog fuel were collected at each of these locations. One bag from each location was frozen in a cold room set at -15°C and the other was left in its natural state.

In the second and third trials the effect of particle size was studied. Bags of hog fuel material were collected at five forest products mills in the Vancouver area, again from mills A and B and from three other mills designated C, D and E. The samples were divided according to the following classifications.

Hog Fuel - mostly bark which went through the hogger as the logs were being peeled. The hog fuel consisted of hemlock bark from mills A, B and E and cedar bark from mills C and D.

Sieved Sawdust - The sawdust was cedar and passed through a half inch sieve. It was collected from mills C and D.

Sawdust and Shavings - This material was cedar and was collected from mills C and D.

In the case of the sieved sawdust samples, after running them at room temperature under the moisture sensor the unused portion in the bags was frozen in a cold room maintained at -15°C for further analysis.

Some green aspen pulp chip samples were obtained from a local pulp research laboratory for moisture content analysis by the new moisture sensor.

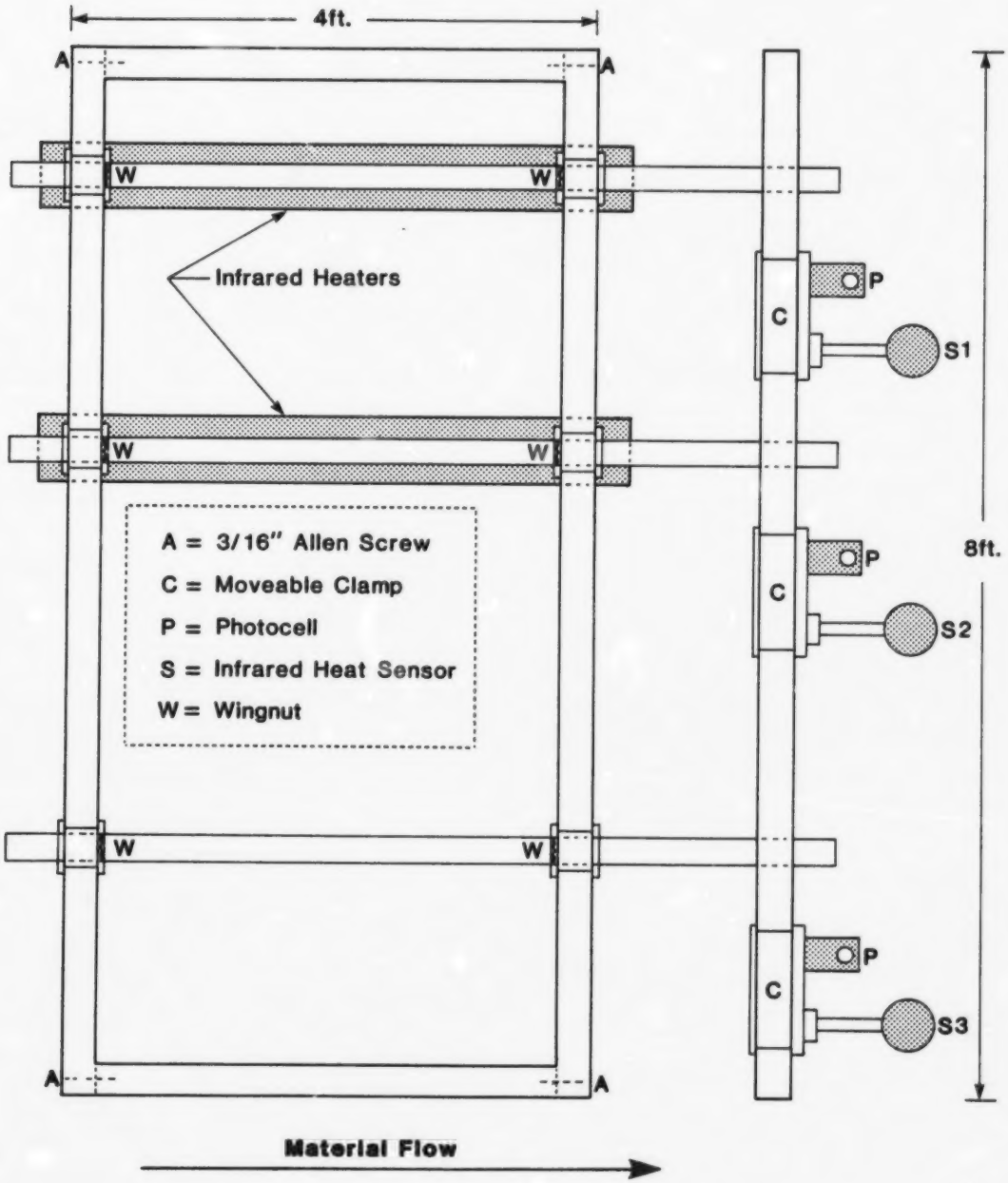
3.2 Method

A moisture measuring system was constructed at Forintek Canada Corp. The top view of this apparatus is shown in Figure 3.2.1. Two 5,000 watt infrared heaters parallel to each other and 19 inches apart were attached to the four by eight foot aluminum metal frame. Three infrared heat sensors and three photocells were also attached to the frame as shown in Figure 3.2.1. Sensor 1 (Figure 3.2.1) was a Telatemp Infrared 44-2MHE Model and Sensors 2 and 3 were Infratrace 800 and 1500 models respectively. The Telatemp infrared 44-2MHE and Infratrace 800 sensors were directly aligned 15 inches in front of the heaters using adjustable clamps and the Infratrace 1500 sensor was used to measure initial temperature. The Infratrace 1500 sensor (S3 in Figure 3.2.1) was 16 inches from the Infratrace 800 sensor (S2).

This moisture measuring system was mounted on a frame over the laboratory's veneer green chain. The system was mounted such that the infrared heaters were two inches above the surface of the hog fuel. Three boxes were constructed from quarter inch plywood with outside dimensions of one by five feet and heights of one, three and six inches. Three compartments were built in each box, having a width of five and a half inches. The compartments were positioned in the box to pass under an infrared sensor as shown in Figure 3.2.1

Figure 3.2.1 Moisture Measuring System

TOP VIEW



For an experimental run, green hog fuel or sawdust material was packed level in each compartment and run underneath the sensors at 50 ft./min. on a conveyor belt system. After the run, samples of approximately 150 g were placed in beakers, weighed immediately and then heated in an air circulating oven set at 105°C until they reached constant weight. The moisture content was then calculated on a green weight basis.

4. RESULTS AND DISCUSSION

A new method developed at Forintek to measure moisture content in unseasoned wood materials (Clarke and Troughton, 1985) is based on a relationship between surface temperature and m.c.

Figure 4.1 shows a typical example of the relationship between surface temperature and m.c. in unseasoned spruce veneer dried at 180°C. At approximately 20 percent m.c. the surface temperature increases at a very rapid rate. This break in the temperature curve corresponds approximately to the fiber saturation point (the point dividing "free" water from the "bound" water). The "bound" water is hydrogen bonded to the cellulose component of wood and is in the zero to 25 percent range and is more strongly bonded than the "free" water. The "free" water is hydrogen bonded to itself and occupies the m.c. region above 25 percent. The rapid rise in temperature in the zero to 20 percent m.c. range occurs since much of the heat energy is being transferred to the wood rather than all of it being consumed in evaporating the water. When the veneer reaches zero percent m.c. the high surface temperature causes inactivation to occur rapidly, due to the acceleration of the chemical oxidation reactions. Thus, in the latter drying stages, the surface temperature could provide important information on the overdrying of the veneer.

The following equation gives the surface temperature rise:

$$Q = (T_f - T_i)\,(S_w W_o + 1 \cdot W_a) + W_a \Delta H_e \quad \text{..... Equ. 1}$$

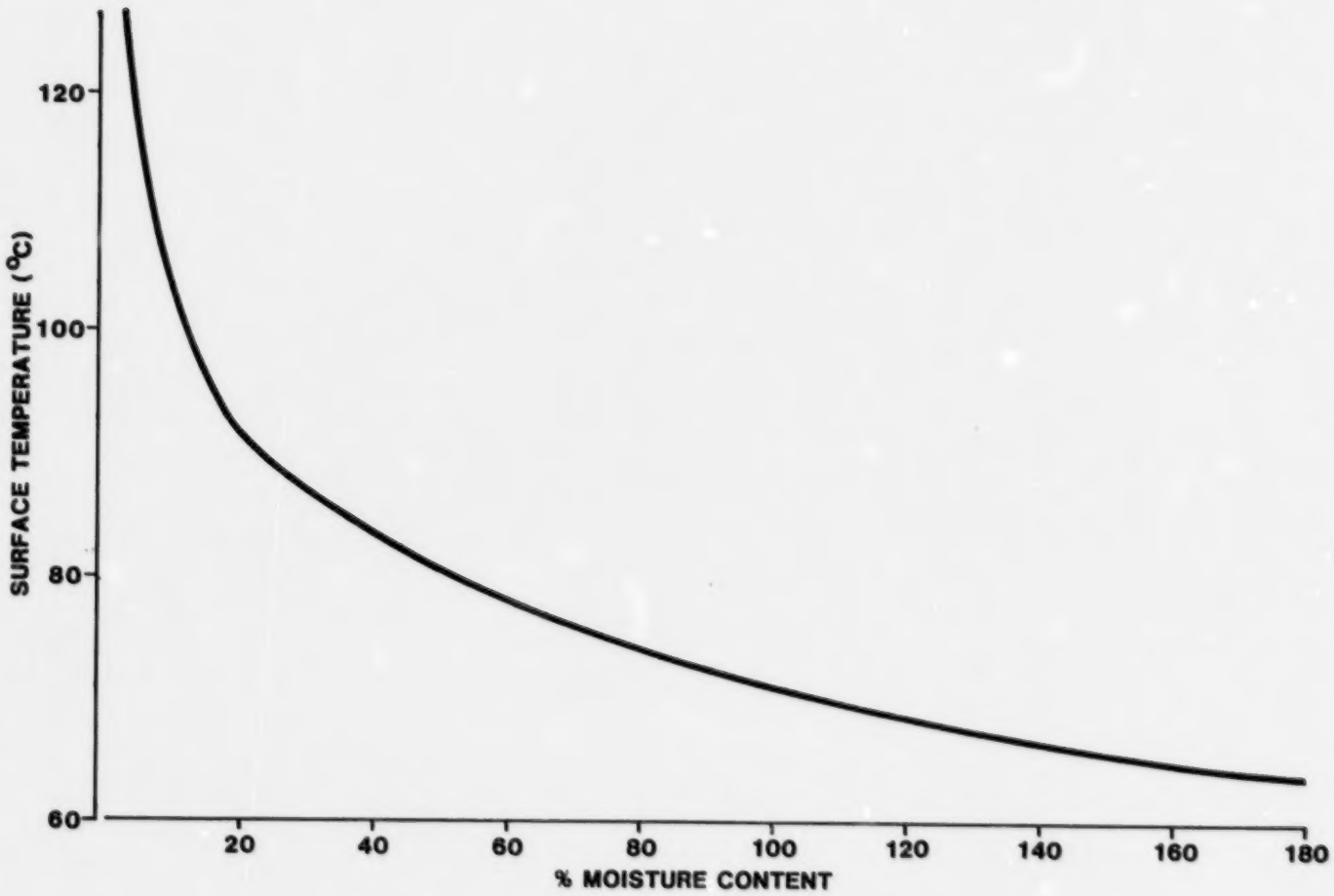


Figure 4.1 Relationship between Veneer Surface Temperature and % Moisture Content.

where: Q = fixed amount of heat

S_w = specific heat of wood (cal/g°C)

1 = specific heat of water (cal/g°C)

W_o = known surface mass of wood

W_a = unknown mass of water

T_i = initial temperature

T_f = final temperature

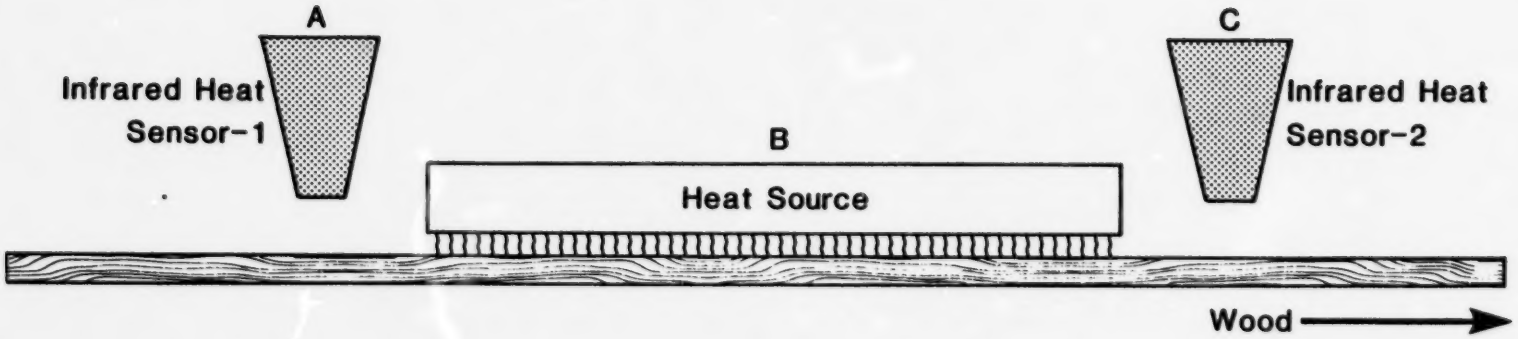
ΔH_e = heat of evaporation, 540 cal/g.

In this equation, the cooling effect from the heat of evaporation plays an important role in controlling temperature rise.

Using the above heating principles, a method was developed to measure the m.c. in unseasoned wood which could then be applied for sorting. A schematic side view of an apparatus used in these experiments to measure m.c. in unseasoned wood is shown in Figure 4.2. A conveyor belt shown in this figure moves the material underneath the infrared heater at a fixed line speed. Thus the infrared heater applies a known amount of energy for a fixed period of time to a surface area along the length of the wood. The two heat sensors determine the intital and final surface temperatures, which are recorded. Good relationships were found for green veneer and lumber (Figures 4.3 and 4.4) when the temperature rise was plotted against m.c.

A new moisture measuring system, based on the above heating principles, was constructed as shown in Figure 3.2.1 and mounted on the Western Laboratory's veneer green chain. The sensors and photocells were interfaced to an IBM-PC microcomputer. A computer program was written for the IBM-PC microcomputer to collect and analyze the temperature data from the three infrared heat sensors. The signal from the photocells indicated when there was experimental material under the sensors and gave the signal to the computer to read and calculate the mean temperature differences. The difference between the mean final and initial temperature, dmean, was used to correlate the green moisture content calculated by the oven dry method.

Figure 4.2 Drawing of Moisture Measurement System



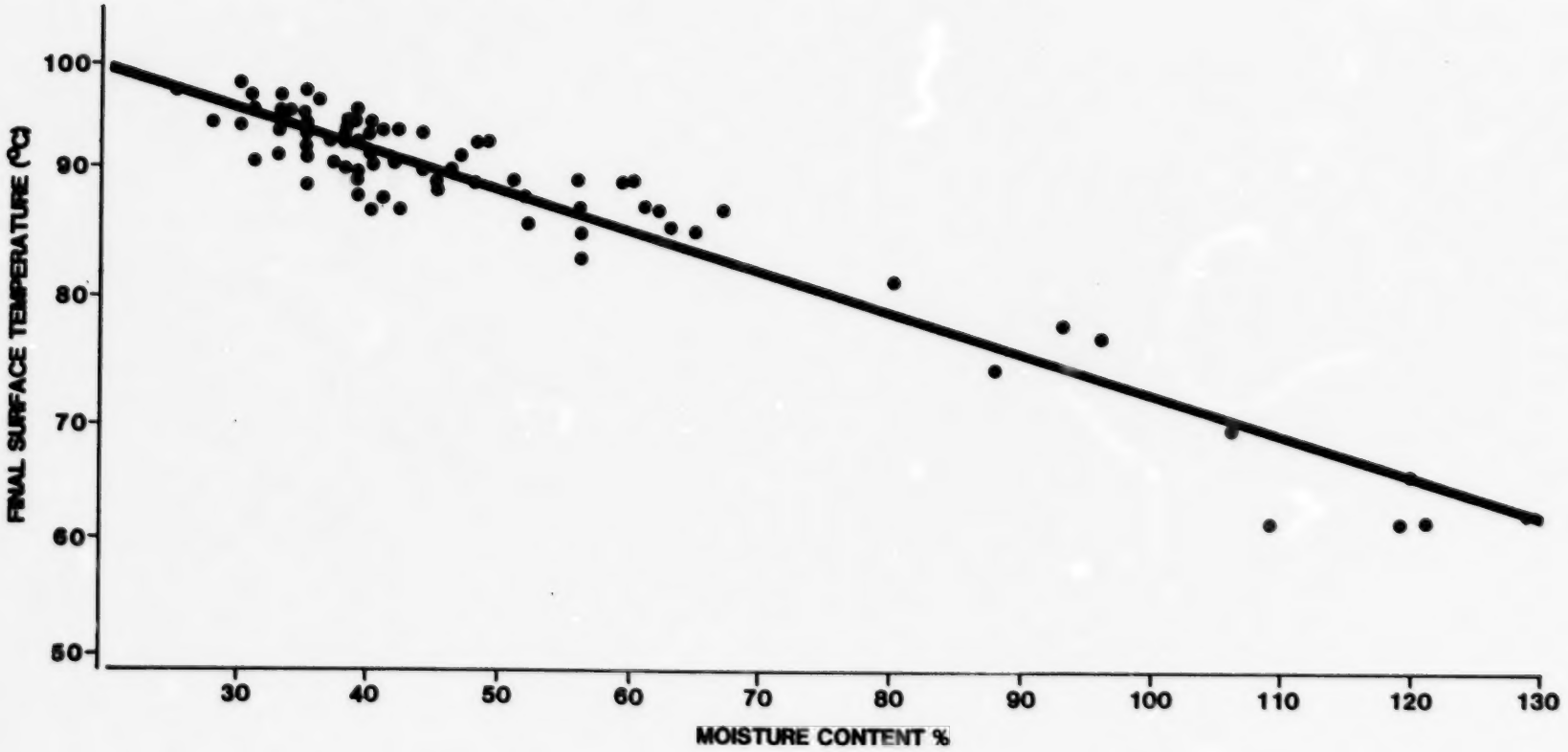


Figure 4.3 Graph showing the relationship between final surface temperature and % moisture content for 1/8 in. spruce veneer.

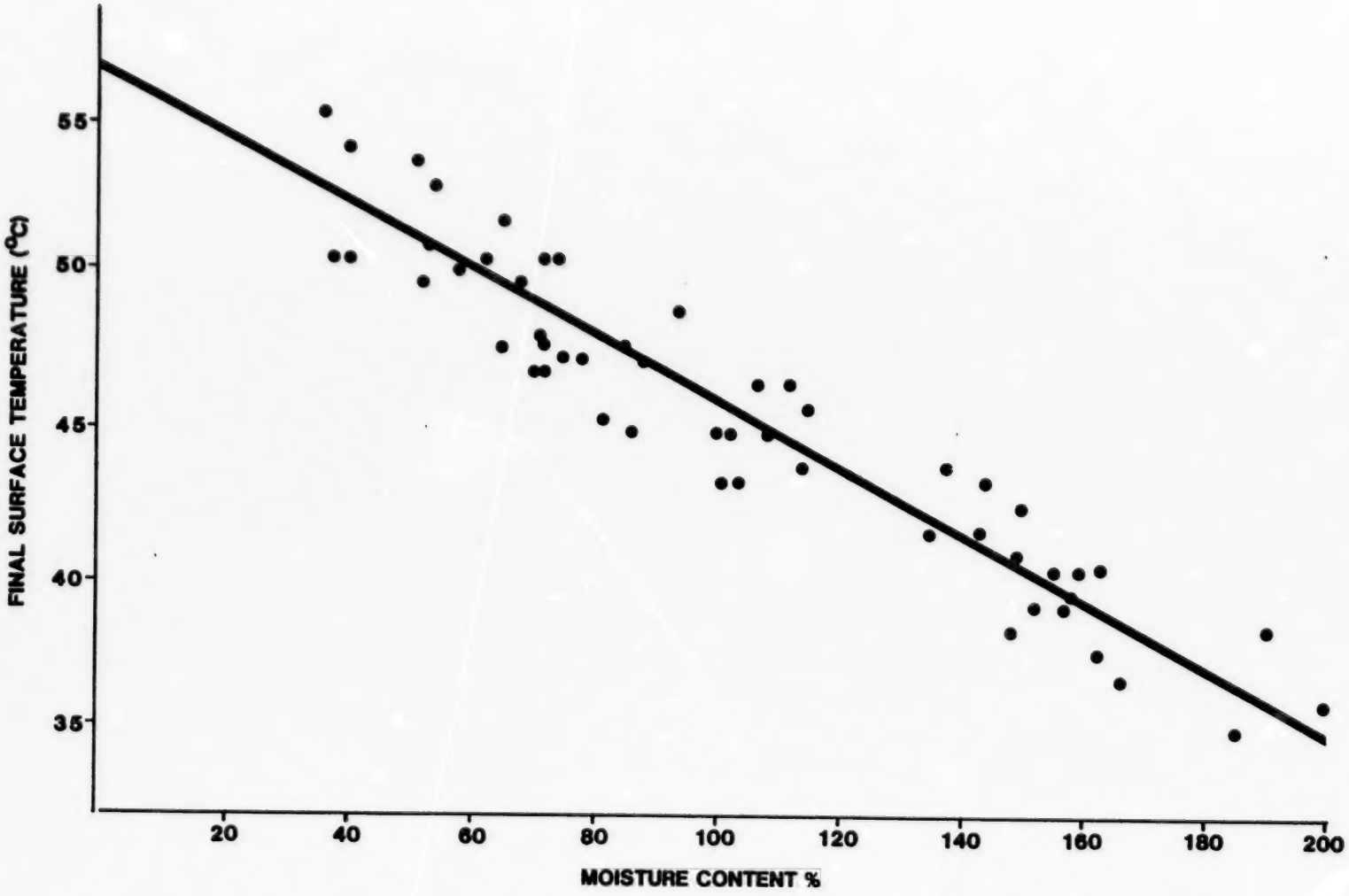


Figure 4.4 Graph showing the relationship between final surface temperature and % moisture content for unseasoned 2X6 in. hem-fir lumber.

In the present work, this new moisture sensor was evaluated for measuring m.c. in different types of hog fuel material and aspen pulp chips. In all the experiments green material (obtained from forest products mills) was used and was not conditioned. A typical site, where the hog fuel was collected, is shown in Figure 4.5. Because the m.c. of the hog fuel material was not controlled, in some experimental runs the m.c. range was very narrow for the samples, less than two percent in some cases, and was too narrow to attempt calculating actual m.c. with temperature rise.

The results for the relationship betwen actual m.c. and temperature rise, dmean, are presented in Appendix A, Figures A.1 to A.18. The temperature rise, dmean, was calculated by the computer by taking the difference between the mean final and initial temperatures, as measured by the infrared heat sensors. The majority of results were obtained for one and three inch depths of different hog fuel materials. However, in one small experimental trial, hog fuel samples were run past the moisture sensors at a six inch depth. The relationship shown in Figure A.5 shows a high correlation for these samples for Sensor 1. The correlations between actual m.c. and dmean for the different types of hog fuel material were very good for both the one and three inch depths of hog fuel materials. In general, the correlations were slightly better for the one inch depth. For example, the correlation coefficients for the one inch depth hog fuel samples (Figures A.1 and A.2) were 0.9258 and 0.8640 for Sensors 1 and 2 respectively, compared to the corresponding coefficients of 0.7704 and 0.7402 for the three inch depth (Figures A.3 and A.4). Similarly, the correlation coefficients for the one inch depth sawdust and shavings samples (Figures A.6 and A.7) were 0.9671 and 0.7932 for Sensors 1 and 2 respectively compared to the corresponding coefficients of 0.8817 and 0.6485 for the three inch depth (Figures A.8 and A.9).

Figure 4.5 Typical Mill Collection Site for Hog Fuel.

Some of the small amount of scatter in the graphs containing the hog fuel samples could be caused by the non-homogeneous nature of the material. It was observed that in some of the hog fuel samples the material was very non-homogeneous, containing large wood particles in the 40 to 45 percent m.c. range and small bark particles in the 60 to 70 percent m.c. range. Thus, if more bark is exposed at the surface, covering up lower m.c. wood particles, the point on the graph would be lower than it should be. Correspondingly, if more wood particles than bark particles were exposed on the surface the point would be higher than it should be.

In general, sensor 1 (Telatemp Model 44-2MHE infrared heat sensor) gave better correlations between actual m.c. and dmean than sensor 2 (Infratrace Model 800 infrared heat sensor). Examples of higher correlation coefficients for sensor 1 compared to sensor 2 were given above for the hog fuel samples. Higher correlations were also found for other types of materials including alder chips (Figures A.13 and A.14) and sawdust and shavings material (Figures A.6 to A.9). Thus, for the sawdust and shavings material, the correlation coefficients for sensor 1 for the one and three inch depths were 0.9671 and 0.8817 respectively, compared to the corresponding coefficients of 0.7932 and 0.6485 respectively for sensor 2. This higher accuracy for sensor 1 could be accounted for by its faster response time to sensing temperature, 0.05 sec., at least twice as fast as sensor 2.

Hog fuel can come in different types and particle sizes ranging from sawdust to bark particles. Sinclair (1984) has conducted studies to process sortyard and logging debris into cleaner, more homogeneous products, suitable as a feedstock for hogged fuel. In the present work the slopes of the best fit-least squares lines varied for the different types of materials. For a given mill situation, calibration lines and tables (between dmean and actual m.c.) should be calculated for the type of materials being used to obtain the most accurate results. Examples of calibration tables are given in Appendix B (Tables B.1 to B.9). The data in these

tables were calculated from the best fit-least squares lines in Figure A.1 to A.18.

For the experimental runs with the frozen material, a bag of frozen hog fuel was quickly taken from the cold storage room to the conveyor line with the moisture sensor. A hammer was used to break up the frozen material and the material was then packed level in each compartment of the one by five foot plywood box described earlier (Section 3.2). After being conveyed underneath the moisture sensor, 150 g samples were removed from the compartments for m.c. analysis (using the oven dry method). The m.c. was calculated on a green weight basis. Unlike the unfrozen material, the preheating has to overcome the heat of fusion of the ice. This cooling effect caused the measured mean temperature difference for the frozen material to be about 2 - 4°C lower than the unfrozen material at a given m.c. The results given in Figures A.15 to A.18 show very good correlations (correlation coefficients all above 0.9) between actual m.c. and dmean for the frozen hog fuel materials. The exception to these high correlations were the frozen sawdust and shavings samples measured by Sensor 2 which showed a correlation coefficient of 0.5205. Again, as for the non-frozen materials, Sensor 1 with a faster response time than Sensor 2 performed better in evaluating the m.c.

5. CONCLUSIONS

5.1 The new moisture sensor showed very good correlations between actual m.c. and temperature rise, dmean, for different types of hog fuel material, including cedar sawdust and shavings, sieved cedar sawdust and cedar and hemlock bark.

5.2 In general, better correlations between actual m.c. and temperature rise were found for the one inch depth hog fuel materials compared to the three inch depth.

5.3 Sensor 1, Telatemp Model 44-2MHE infrared heat sensor, gave more accurate m.c. measurements than Sensor 2, Infratrace Model 800 infrared heat sensor.

5.4 The new moisture sensor performed well for frozen hog fuel materials as indicated by the good correlations between actual m.c. and temperature rise.

6. RECOMMENDATION

The results in this report show there is good potential in measuring m.c. in hog fuel materials using a new moisture sensor incorporating infrared point heat sensors. It is recommended that a commercial prototype moisture sensor using the infrared point sensors be built and evaluated under mill conditions. It has been noted that, whereas the infrared point sensors scan one point only, a high temperature infrared linescanner has recently been developed which can scan temperatures along a line and therefore has the capability of scanning a much larger area than the point sensors. This should allow for even more accurate measurements of the average m.c. in hog fuel materials. It is also recommended that further work be initiated to develop a low temperature infrared linescanner which can be interfaced with the new moisture sensor and evaluated for measuring m.c. in hog fuel materials.

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APPENDIX A

EIGHTEEN FIGURES SHOWING THE RELATIONSHIP BETWEEN ACTUAL MOISTURE CONTENT AND dMEAN FOR DIFFERENT HOG FUEL MATERIALS

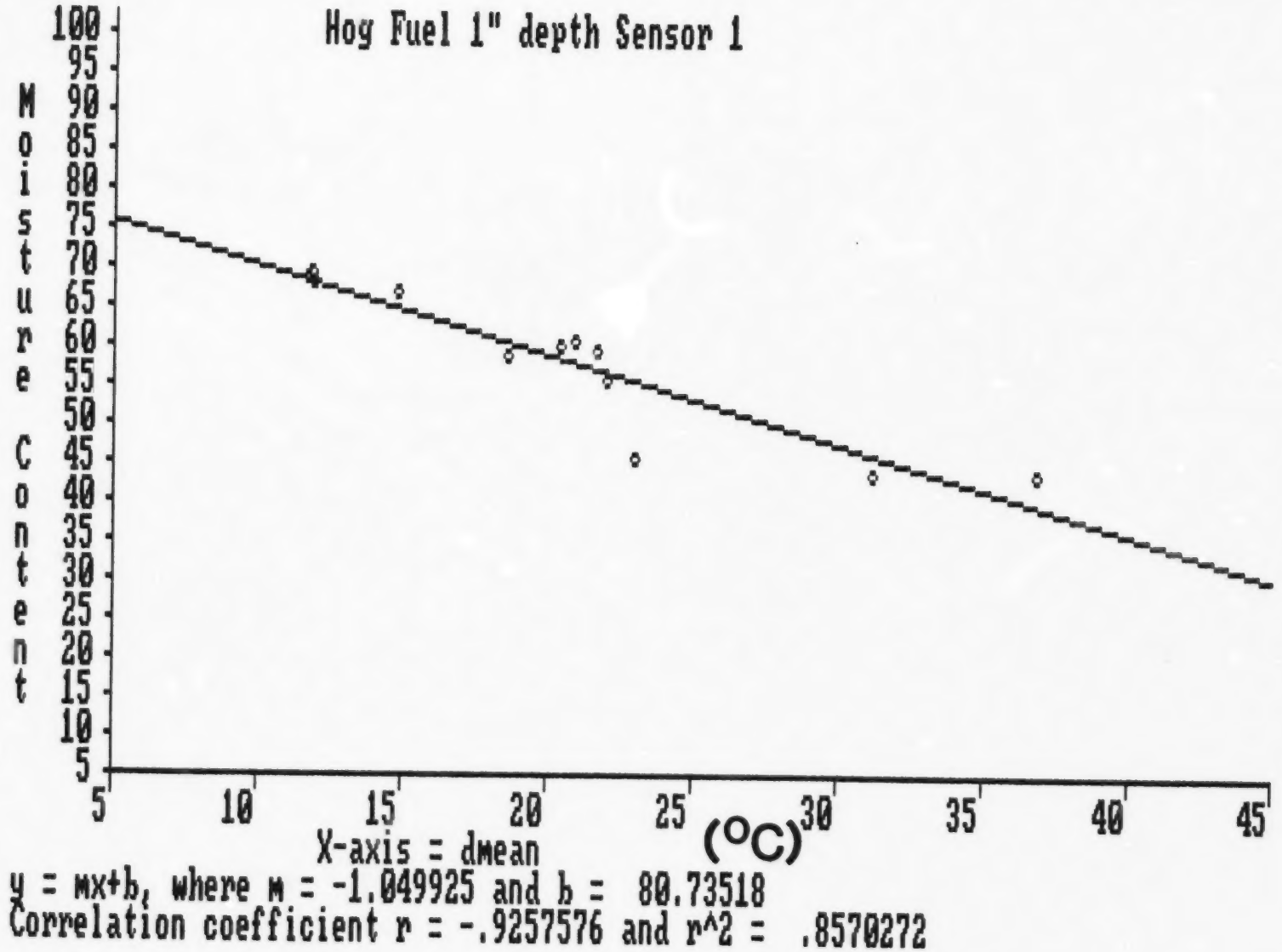

Figure A.1 The Relationship Between Actual Moisture Content and dMean for Hog Fuel, One Inch Depth, Sensor 2

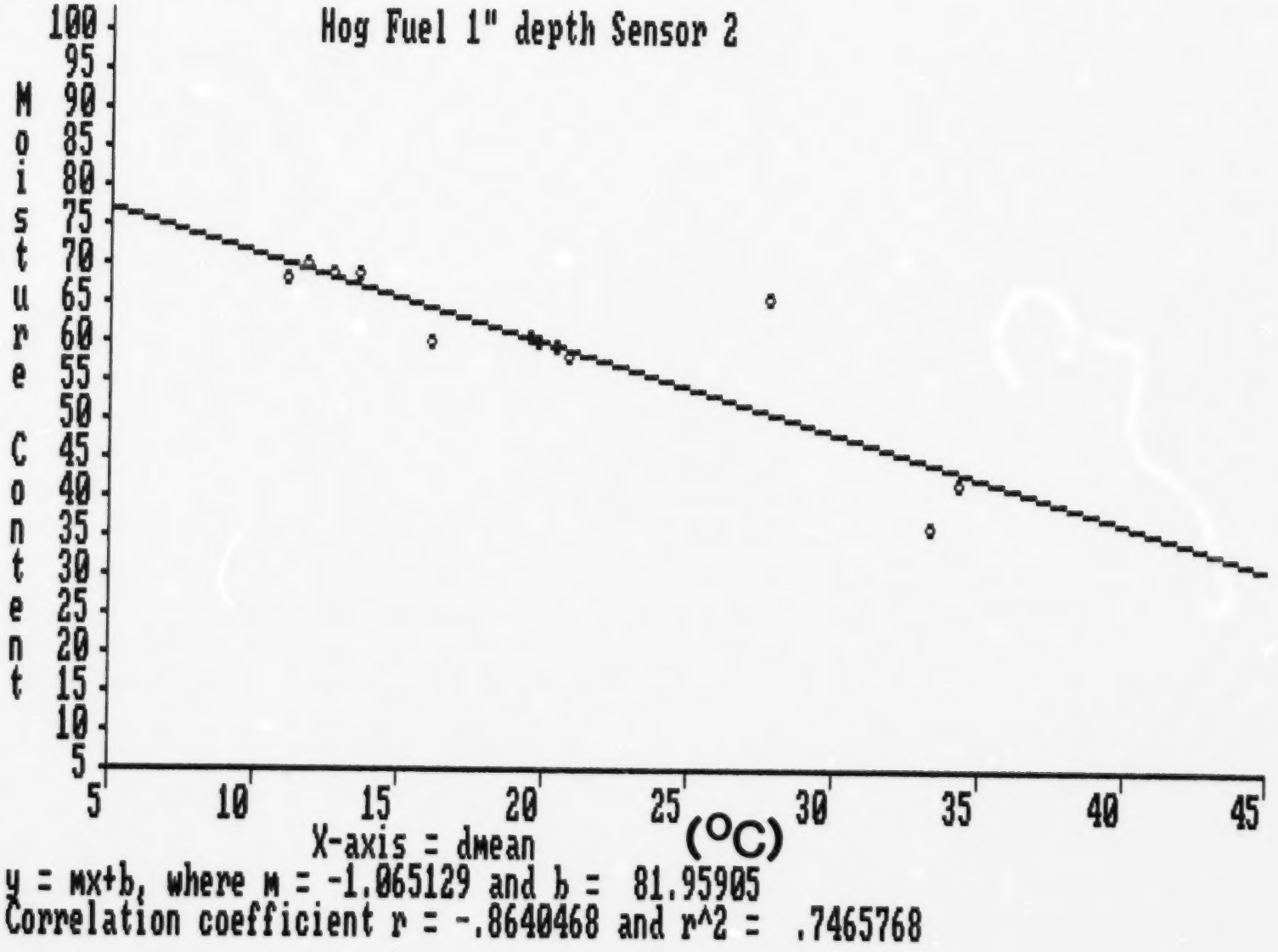

Figure A.2 The Relationship Between Actual Moisture Content and dMean for Hog Fuel, One Inch Depth, Sensor 2.

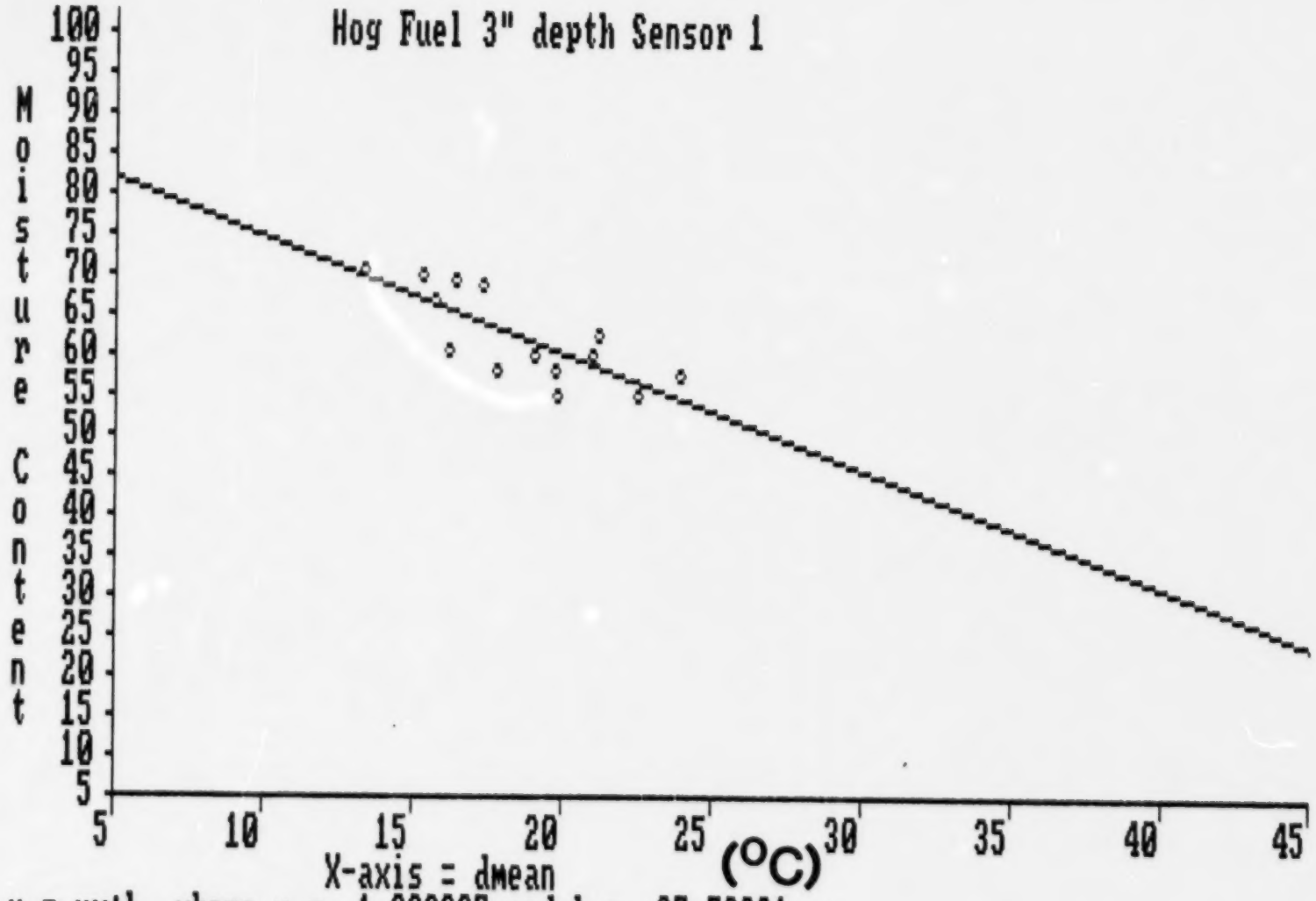

Figure A.3 The Relationship Between Actual Moisture Content and dMean for Hog Fuel, Three Inch Depth, Sensor 1.

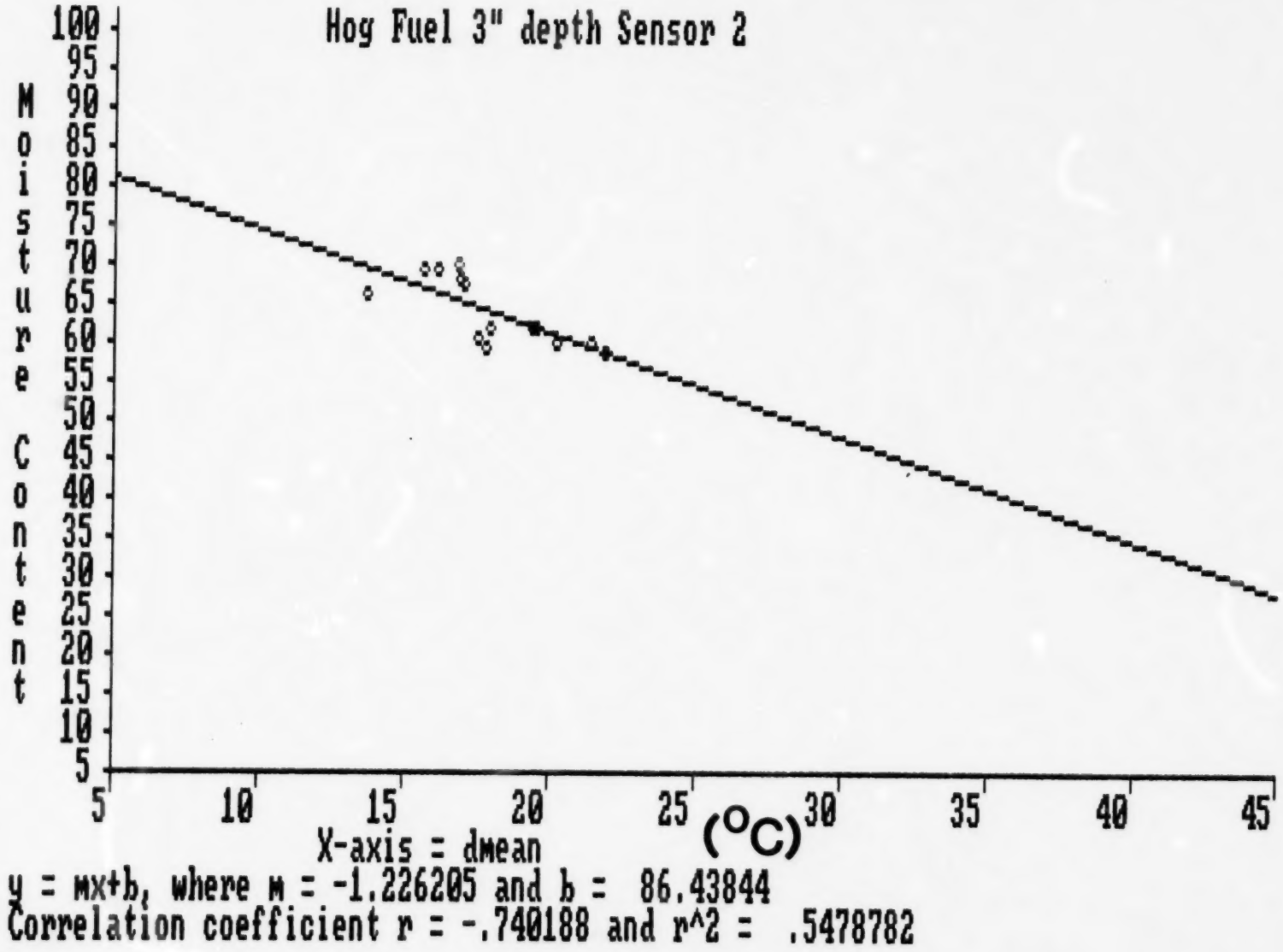

Figure A.4 The Relationship Between Actual Moisture Content and dMean for Hog Fuel, Three Inch Depth, Sensor 2.

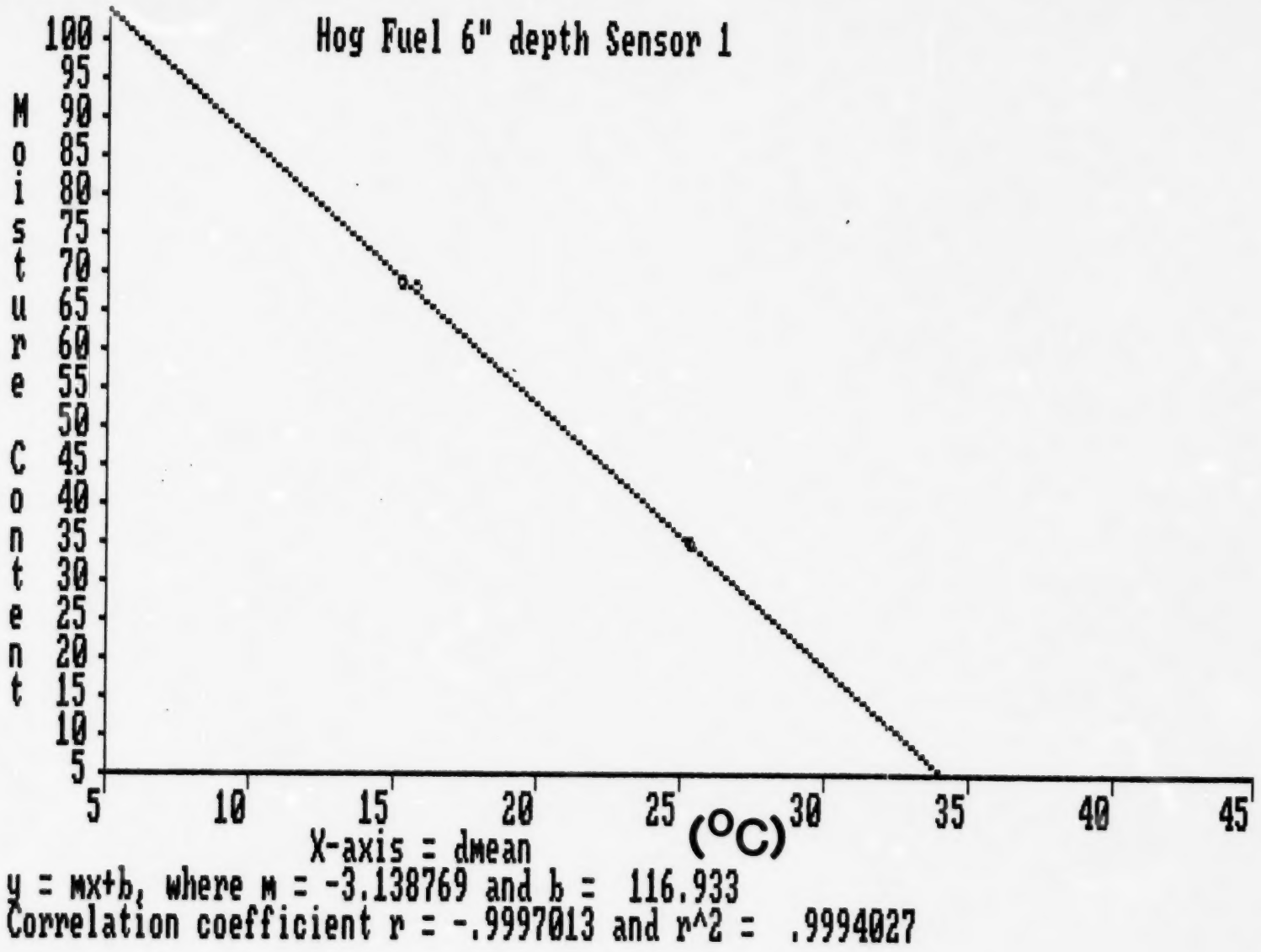

Figure A.5 The Relationship Between Actual Moisture Content and dMean for Hog Fuel, Six Inch Depth, Sensor 1.

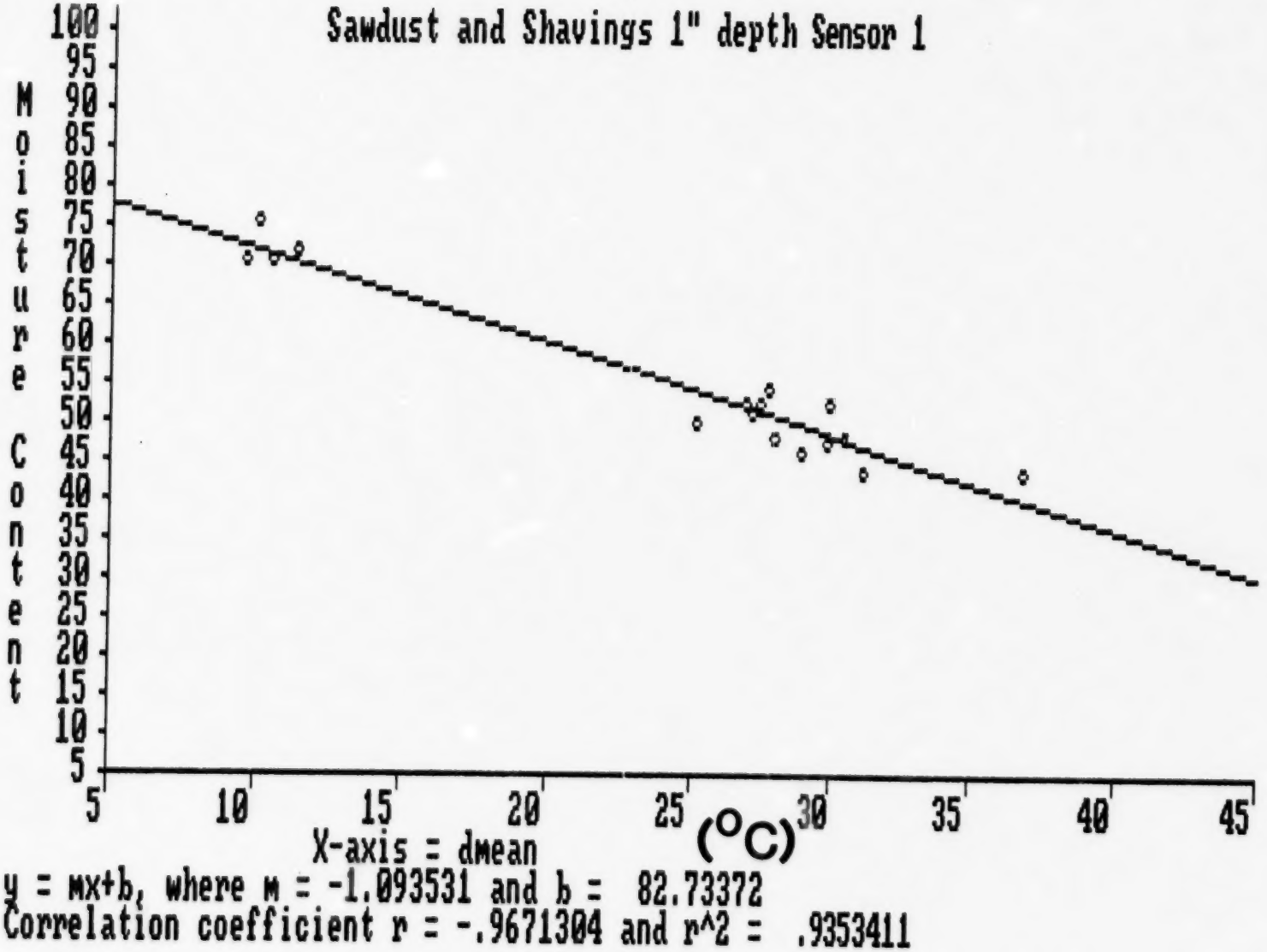

Figure A.6 The Relationship Between Actual Moisture Content and dMean for Sawdust and Shavings, One Inch Depth, Sensor 1.

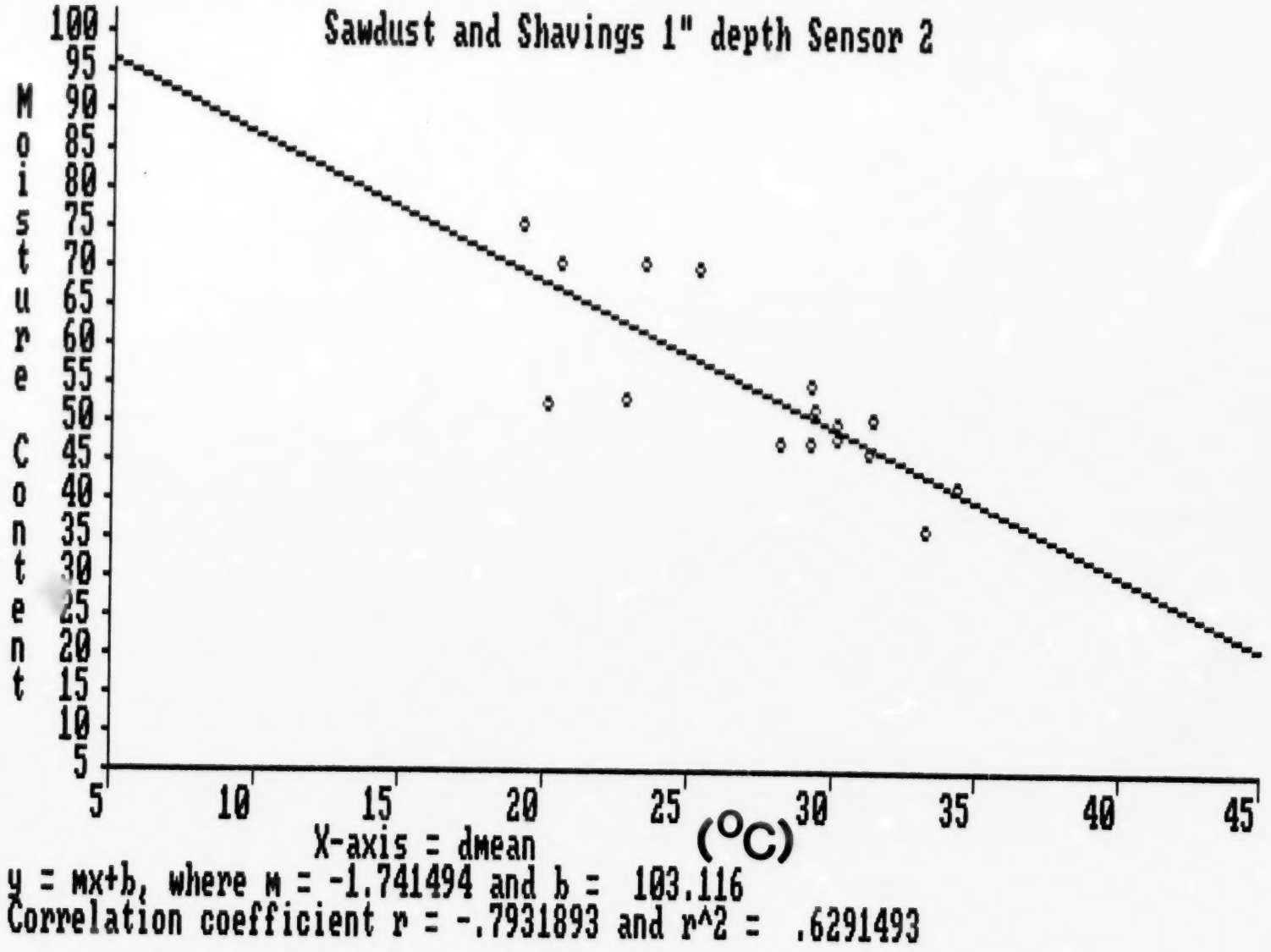

Figure A.7 The Relationship Between Actual Moisture Content and dMean for Sawdust and Shavings, One Inch Depth, Sensor 2.

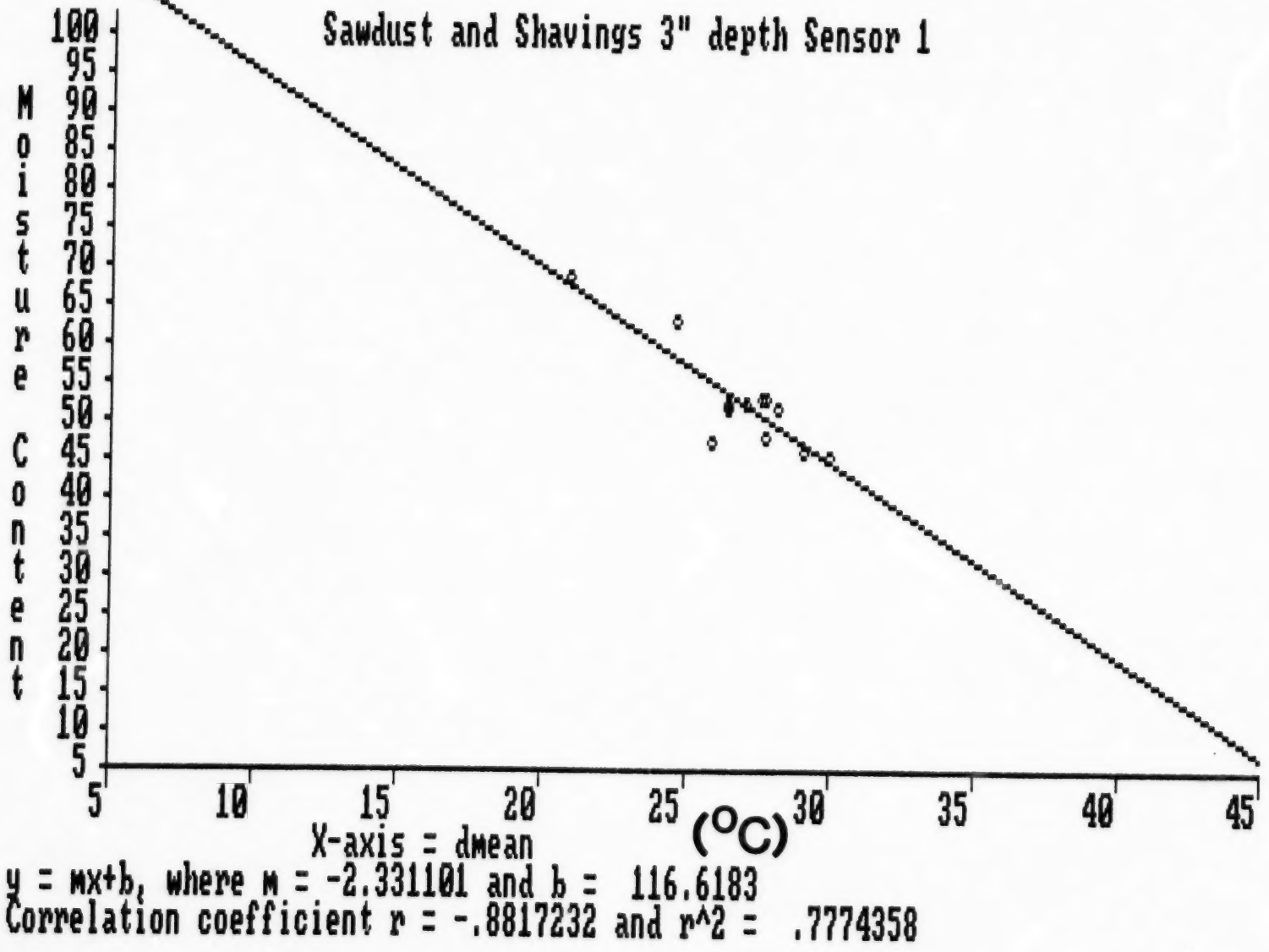

Figure A.8 The Relationship Between Actual Moisture Content and dMean for Sawdust and Shavings, Three Inch Depth, Sensor 1.

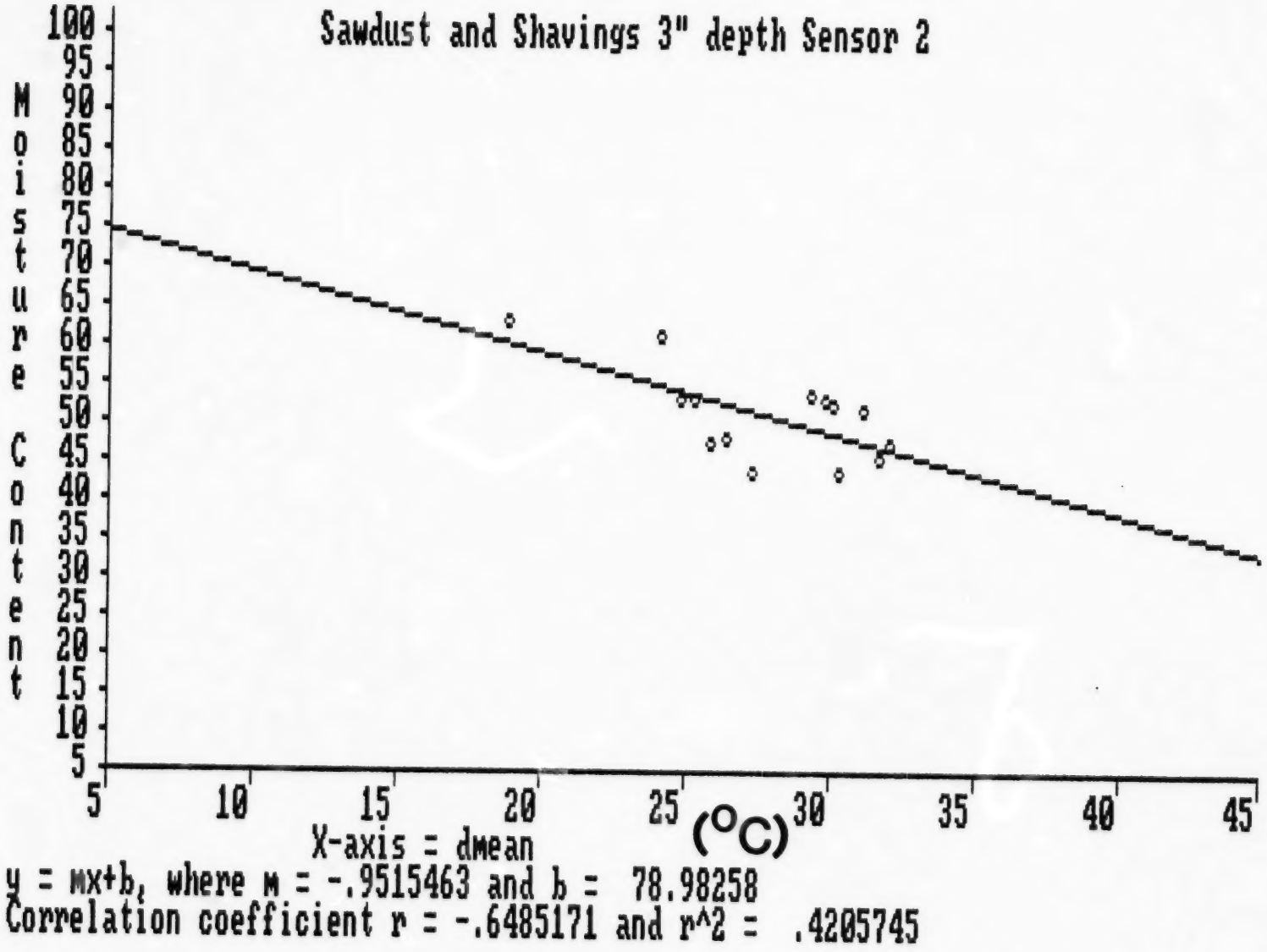

Figure A.9 The Relationship Between Actual Moisture Content and dMean for Sawdust and Shavings, Three Inch Depth, Sensor 2.

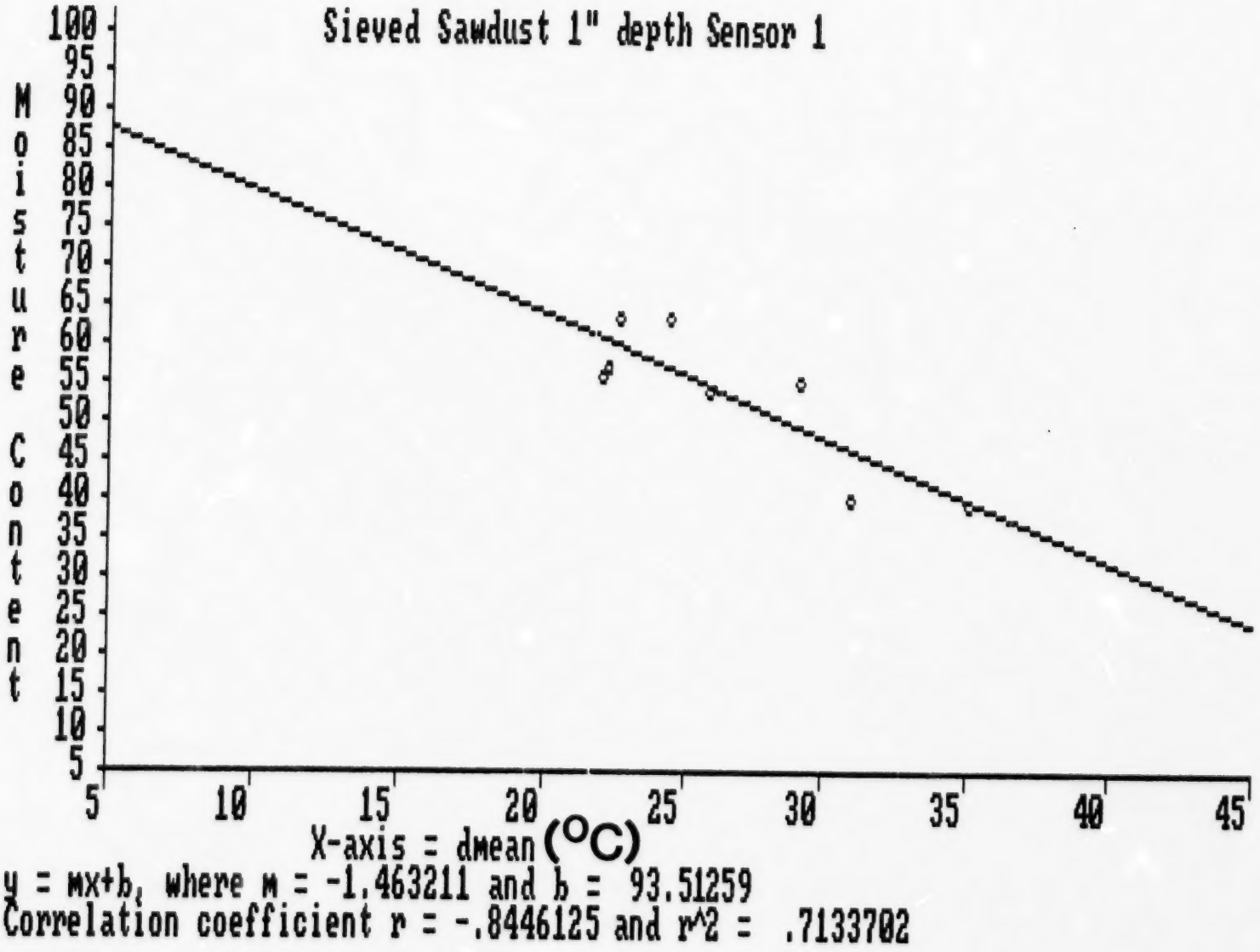

Figure A.10 The Relationship Between Actual Moisture Content and dMean for Sieved Sawdust, One Inch Depth, Sensor 1.

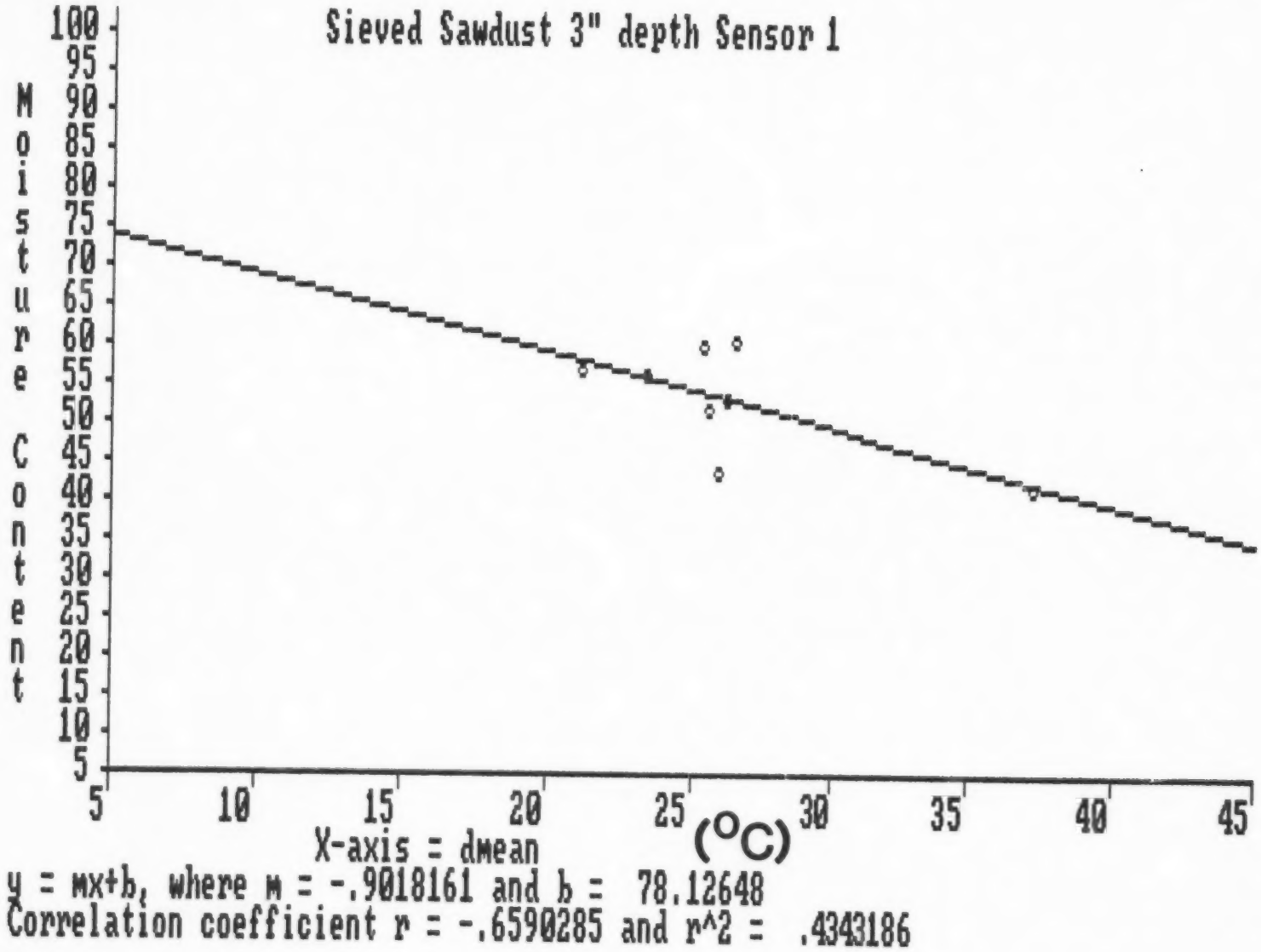

Figure A.11 The Relationship Between Actual Moisture Content and dMean for Sieved Sawdust, Three Inch Depth, Sensor 1.

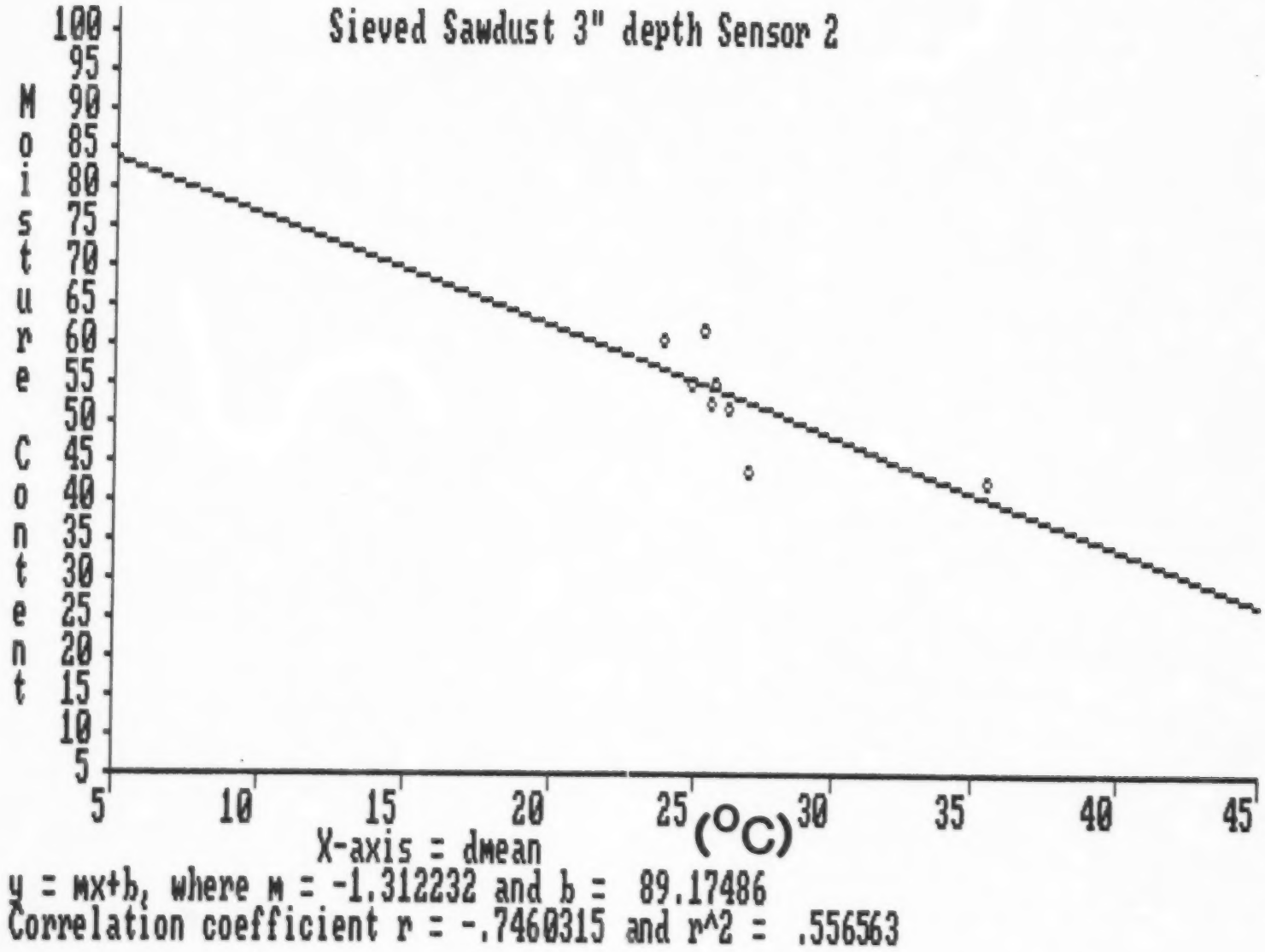

Figure A.12 The Relationship Between Actual Moisture Content and dMean for Sieved Sawdust, Three Inch Depth, Sensor 2.

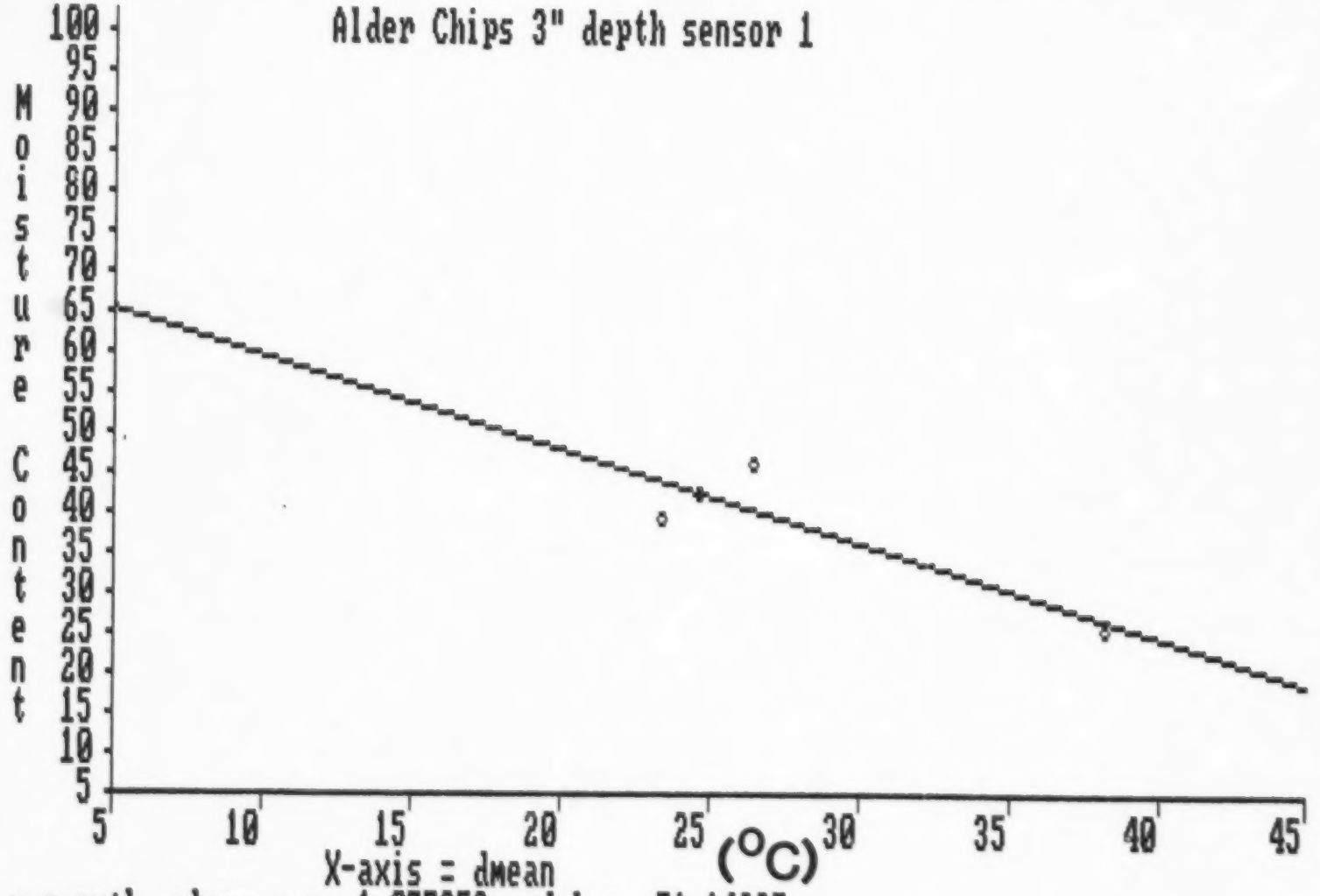

Figure A.13 The Relationship Between Actual Moisture Content and dMean for Alder Chips, Three Inch Depth, Sensor 1.

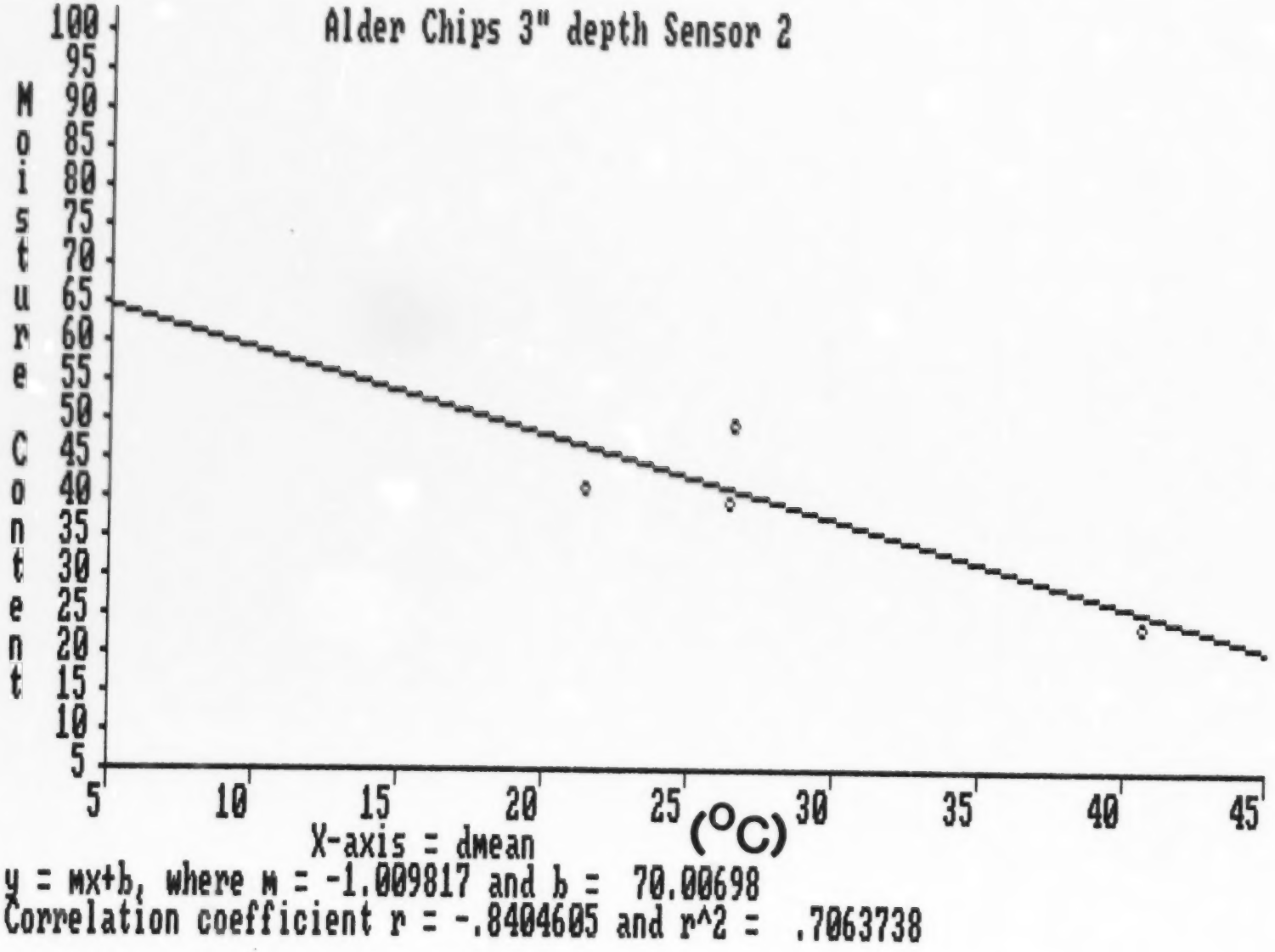

Figure A.14 The Relationship Between Actual Moisture Content and dMean for Alder Chips, Three Inch Depth, Sensor 2.

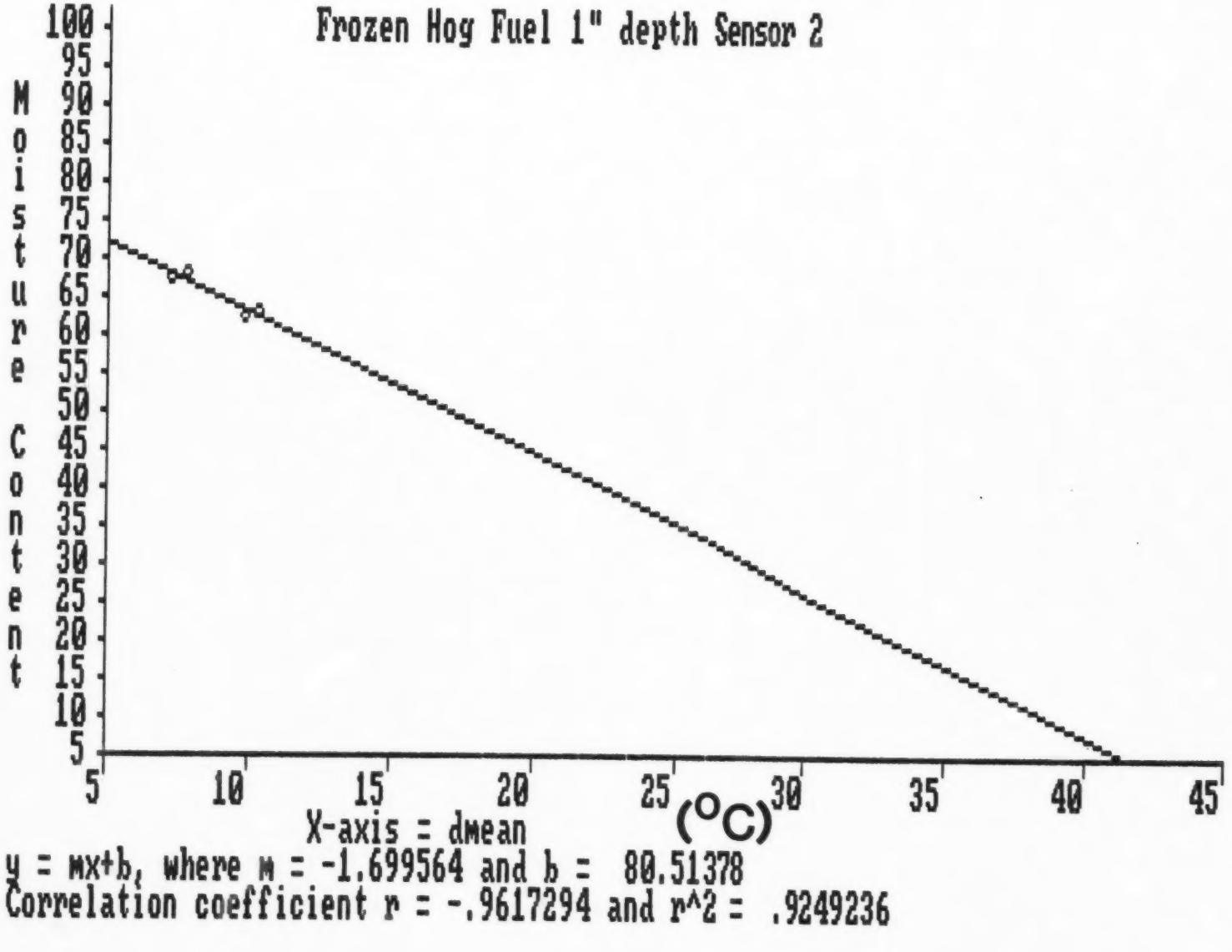

Figure A.15 The Relationship Between Actual Moisture Content and dMean for Frozen Hog Fuel, One Inch Depth, Sensor 2.

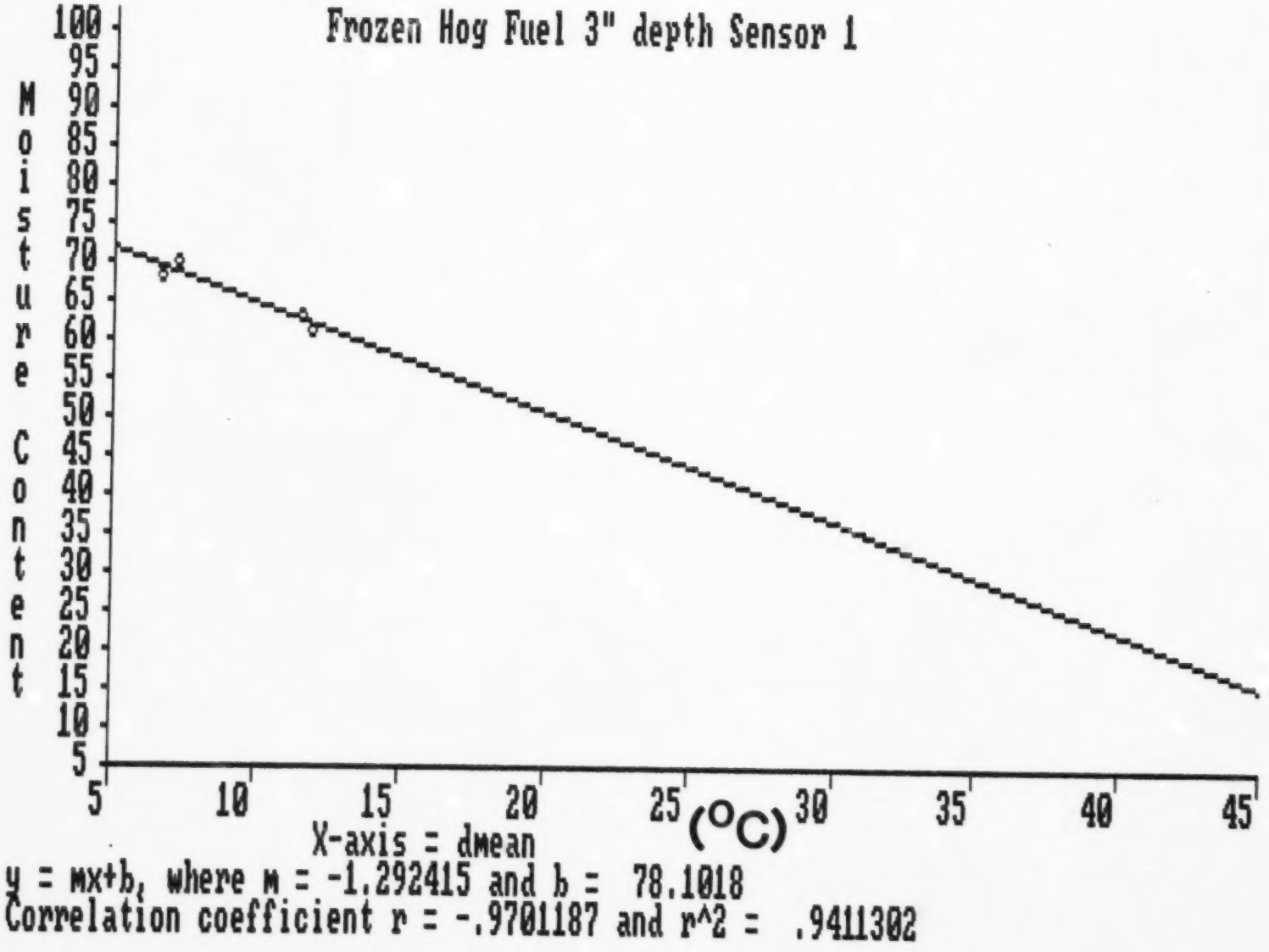

Figure A.16 The Relationship Between Actual Moisture Content and dMean for Frozen Hog Fuel, Three Inch Depth, Sensor 1.

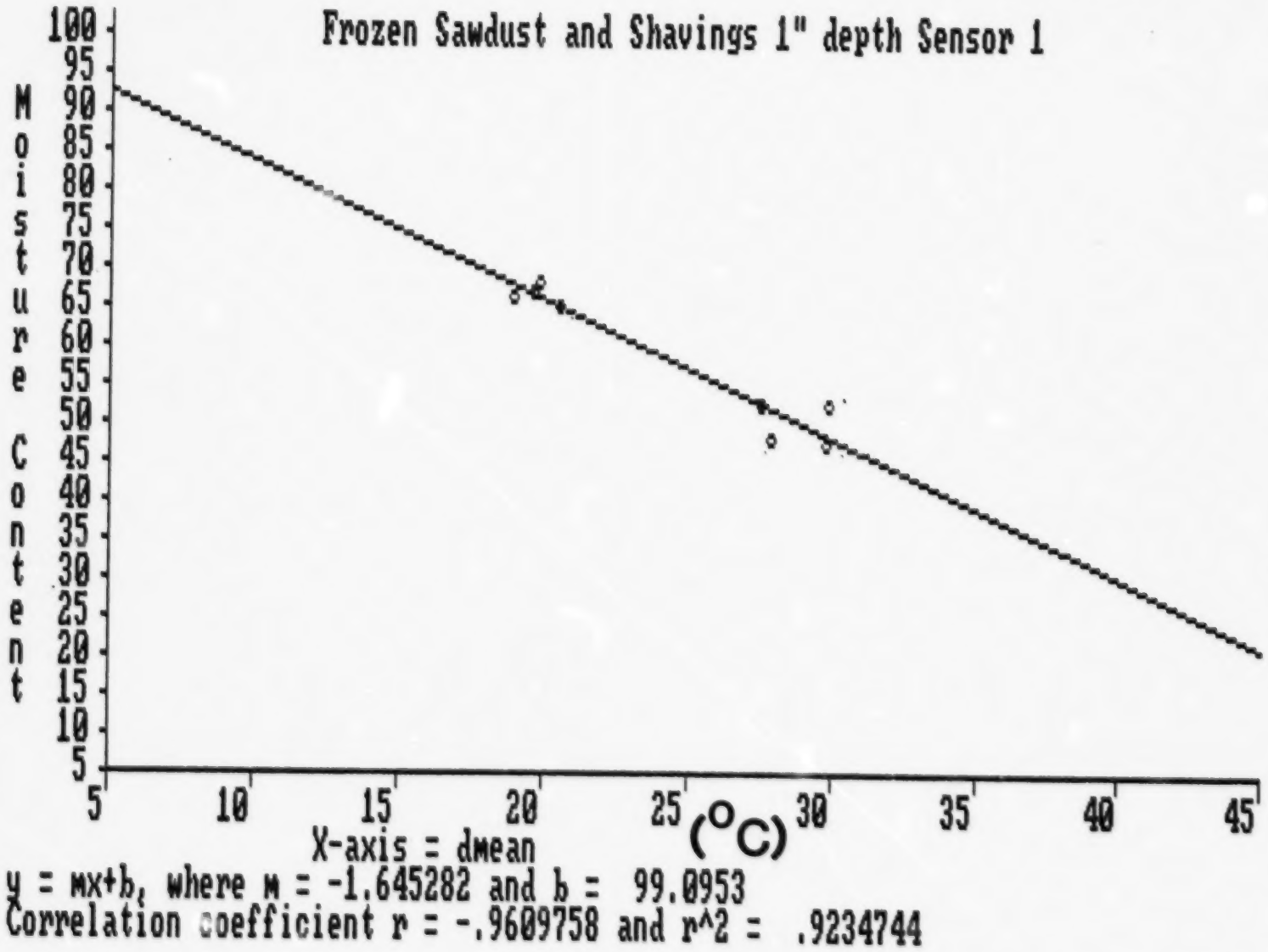

Figure A.17 The Relationship Between Actual Moisture Content and dMean for Frozen Sawdust and Shavings, One Inch Depth, Sensor 1.

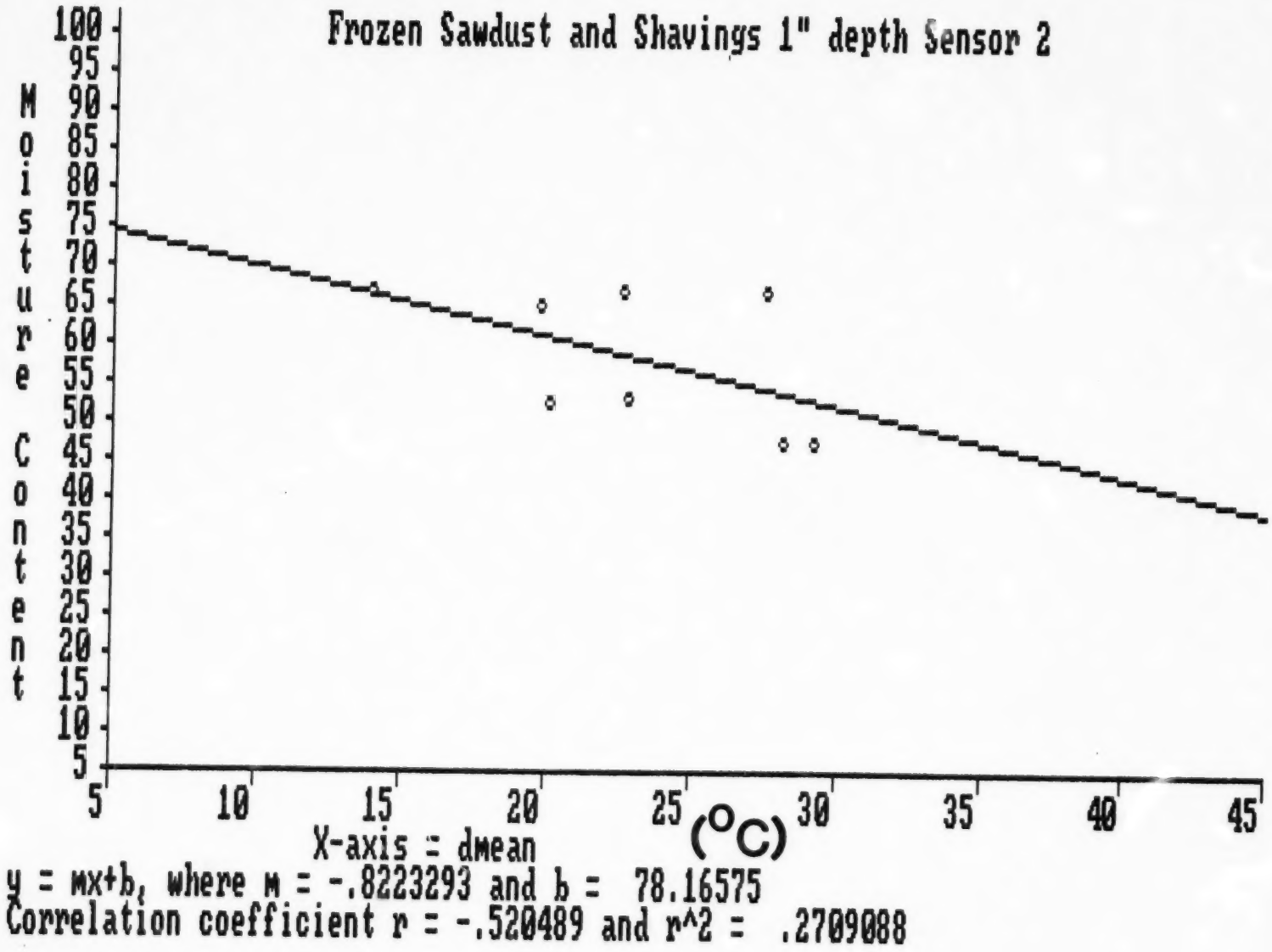

Figure A.18 The Relationship Between Actual Moisture Content and dMean for Frozen Sawdust and Shavings, One Inch Depth, Sensor 2.

APPENDIX B

CALIBRATION TABLES FOR ACTUAL MOISTURE CONTENT AND dMEAN VALUES

(All dMean values are ^{o}C for following nine tables)

TABLE 1 (Hogfuel)

Calibration Table for Sensor 1 (dMean and % M.C.)

dmean	1" depth %m.c.	3" depth %m.c.	6" depth %m.c.
1	80.3	85.2	
2	79.2	84.0	
3	78.1	82.8	
4	76.9	81.5	
5	75.8	80.3	
6	74.7	79.1	
7	73.5	77.9	98.1
8	72.4	76.6	95.0
9	71.3	75.4	91.8
10	70.1	74.2	88.7
11	69.0	73.0	85.5
12	67.9	71.7	82.4
13	66.8	70.5	79.3
14	65.6	69.3	76.1
15	64.5	68.0	73.0
16	63.4	66.8	69.9
17	62.2	65.6	66.7
18	61.1	64.4	63.6
19	60.0	63.1	60.4
20	58.8	61.9	57.3
21	57.7	60.7	54.2
22	56.6	59.5	51.0
23	55.4	58.2	47.9
24	54.3	57.0	44.7
25	53.2	55.8	41.6
26	52.1	54.6	38.5
27	50.9	53.3	35.3
28	49.8	52.1	32.2
29	48.7	50.9	29.0
30	47.5	49.7	25.9
31	46.4	48.4	22.8
32	45.3	47.2	19.6
33	44.1	46.0	16.5
34	43.0	44.7	13.4
35	41.9	43.5	10.2
36	40.7	42.3	7.1
37	39.6	41.1	3.9
38	38.5	39.8	0.8
39	37.4	38.6	
40	36.2	37.4	
41	35.1	36.2	
42	34.0	34.9	
43	32.8	33.7	
44	31.7	32.5	
45	30.6	31.3	

TABLE 2 (Hogfuel)

Calibration Table for Sensor 2 (dMean and % M.C.)

dmean	1" depth % m.c.	3" depth % m.c.
1	77.0	86.4
2	76.0	85.0
3	75.0	83.7
4	74.0	82.4
5	73.0	81.0
6	72.0	79.7
7	70.9	78.4
8	69.9	77.0
9	68.9	75.7
10	67.9	74.3
11	66.9	73.0
12	65.9	71.7
13	64.8	70.3
14	63.8	69.0
15	62.8	67.7
16	61.8	66.3
17	60.8	65.0
18	59.8	63.6
19	58.7	62.3
20	57.7	61.0
21	56.7	59.6
22	55.7	58.3
23	54.7	56.9
24	53.7	55.6
25	52.6	54.3
26	51.6	52.9
27	50.6	51.6
28	49.6	50.3
29	48.6	48.9
30	47.6	47.6
31	46.5	46.2
32	45.5	44.9
33	44.5	43.6
34	43.5	42.2
35	42.5	40.9
36	41.5	39.5
37	40.4	38.2
38	39.4	36.9
39	38.4	35.5
40	37.4	34.2
41	36.4	32.9
42	35.4	31.5
43	34.3	30.2
44	33.3	28.8
45	32.3	27.5

TABLE 3 (Sawdust and Shavings)

Calibration Table for Sensor 1 (dMean and % M.C.)

dmean	1" depth % m.c.	3" depth % m.c.
1	81.6	78.3
2	80.5	77.5
3	79.5	76.6
4	78.4	75.7
5	77.3	74.8
6	76.2	74.0
7	75.1	73.1
8	74.0	72.2
9	72.9	71.3
10	71.8	70.5
11	70.7	69.6
12	69.6	68.7
13	68.5	67.8
14	67.4	67.0
15	66.3	66.1
16	65.2	65.2
17	64.1	64.3
18	63.1	63.4
19	62.0	62.6
20	60.9	61.7
21	59.8	60.8
22	58.7	59.9
23	57.6	59.1
24	56.5	58.2
25	55.4	57.3
26	54.3	56.4
27	53.2	55.6
28	52.1	54.7
29	51.0	53.8
30	49.9	52.9
31	48.8	52.1
32	47.7	51.2
33	46.6	50.3
34	45.6	49.4
35	44.5	48.6
36	43.4	47.7
37	42.3	46.8
38	41.2	45.9
39	40.1	45.1
40	39.0	44.2
41	37.9	43.3
42	36.8	42.4
43	35.7	41.5
44	34.6	40.7
45	33.5	39.8

TABLE 4 (Sawdust and Shavings)

Calibration Table for Sensor 2 (dMean and % M.C.)

dmean	1" depth %m.c.	3" depth %m.c.
1		74.9
2	99.6	74.1
3	97.9	73.3
4	96.2	72.6
5	94.4	71.8
6	92.7	71.0
7	90.9	70.2
8	89.2	69.5
9	87.4	68.7
10	85.7	67.9
11	84.0	67.2
12	82.2	66.4
13	80.5	65.6
14	78.7	64.9
15	77.0	64.1
16	75.3	63.3
17	73.5	62.6
18	71.8	61.8
19	70.0	61.0
20	68.3	60.3
21	66.5	59.5
22	64.8	58.7
23	63.1	58.0
24	61.3	57.2
25	59.6	56.4
26	57.8	55.7
27	56.1	54.9
28	54.4	54.1
29	52.6	53.4
30	50.9	52.6
31	49.1	51.8
32	47.4	51.0
33	45.6	50.3
34	43.9	49.5
35	42.2	48.7
36	40.4	48.0
37	38.7	47.2
38	36.9	46.4
39	35.2	45.7
40	33.5	44.9
41	31.7	44.1
42	30.0	43.4
43	28.2	42.6
44	26.5	41.8
45	24.7	41.1

TABLE 5 (Sieved Sawdust)

Calibration Table for Sensor 1 (dMean and % M.C.)

dmean	1" depth % m.c.	3" depth % m.c.
1	92.0	77.2
2	90.6	76.3
3	89.1	75.4
4	87.7	74.5
5	86.2	73.6
6	84.7	72.7
7	83.3	71.8
8	81.8	70.9
9	80.3	70.0
10	78.9	69.1
11	77.4	68.2
12	76.0	67.3
13	74.5	66.4
14	73.0	65.5
15	71.6	64.6
16	70.1	63.7
17	68.6	62.8
18	67.2	61.9
19	65.7	61.0
20	64.2	60.1
21	62.8	59.2
22	61.3	58.3
23	59.9	57.4
24	58.4	56.5
25	56.9	55.6
26	55.5	54.7
27	54.0	53.8
28	52.5	52.9
29	51.1	52.0
30	49.6	51.1
31	48.2	50.2
32	46.7	49.3
33	45.2	48.4
34	43.8	47.5
35	42.3	46.6
36	40.8	45.7
37	39.4	44.8
38	37.9	43.9
39	36.4	43.0
40	35.0	42.1
41	33.5	41.2
42	32.1	40.3
43	30.6	39.3
44	29.1	38.4
45	27.7	37.5

TABLE 6 (Sieved Sawdust)

Calibration Table for Sensor 2 (dMean and % M.C.)

dmean	3" depth % m.c.
1	87.9
2	86.6
3	85.2
4	83.9
5	82.6
6	81.3
7	80.0
8	78.7
9	77.4
10	76.1
11	74.7
12	73.4
13	72.1
14	70.8
15	69.5
16	68.2
17	66.9
18	65.6
19	64.2
20	62.9
21	61.6
22	60.3
23	59.0
24	57.7
25	56.4
26	55.1
27	53.7
28	52.4
29	51.1
30	49.8
31	48.5
32	47.2
33	45.9
34	44.6
35	43.2
36	41.9
37	40.6
38	39.3
39	38.0
40	36.7
41	35.4
42	34.1
43	32.7
44	31.4
45	30.1

TABLE 7 (Alder Chips)

Calibration Table for Sensors 1 and 2 (dMean and % M.C.)

dmean	Sensor 1 3" depth %m.c.	Sensor 2 3" depth %m.c.
1	70.1	69.0
2	69.0	68.0
3	67.9	67.0
4	66.8	66.0
5	65.8	65.0
6	64.7	63.9
7	63.6	62.9
8	62.5	61.9
9	61.5	60.9
10	60.4	59.9
11	59.3	58.9
12	58.2	57.9
13	57.1	56.9
14	56.1	55.9
15	55.0	54.9
16	53.9	53.8
17	52.8	52.8
18	51.8	51.8
19	50.7	50.8
20	49.6	49.8
21	48.5	48.8
22	47.4	47.8
23	46.4	46.8
24	45.3	45.8
25	44.2	44.8
26	43.1	43.8
27	42.1	42.7
28	41.0	41.7
29	39.9	40.7
30	38.8	39.7
31	37.8	38.7
32	36.7	37.7
33	35.6	36.7
34	34.5	35.7
35	33.4	34.7
36	32.4	33.7
37	31.3	32.6
38	30.2	31.6
39	29.1	30.6
40	28.1	29.6
41	27.0	28.6
42	25.9	27.6
43	24.8	26.6
44	23.7	25.6
45	22.7	24.6

TABLE 8 (Frozen Hogfuel)

Calibration Table for Sensors 1 and 2 (dMean and % M.C.)

dmean	Sensor 1 1" depth %m.c.	Sensor 2 3" depth %m.c.
1	78.8	76.8
2	77.1	75.5
3	75.4	74.2
4	73.7	72.9
5	72.0	71.6
6	70.3	70.3
7	68.6	69.1
8	66.9	67.8
9	65.2	66.5
10	63.5	65.2
11	61.8	63.9
12	60.1	62.6
13	58.4	61.3
14	56.7	60.0
15	55.0	58.7
16	53.3	57.4
17	51.6	56.1
18	49.9	54.8
19	48.2	53.5
20	46.5	52.3
21	44.8	51.0
22	43.1	49.7
23	41.4	48.4
24	39.7	47.1
25	38.0	45.8
26	36.3	44.5
27	34.6	43.2
28	32.9	41.9
29	31.2	40.6
30	29.5	39.3
31	27.8	38.0
32	26.1	36.7
33	24.4	35.5
34	22.7	34.2
35	21.0	32.9
36	19.3	31.6
37	17.6	30.3
38	15.9	29.0
39	14.2	27.7
40	12.5	26.4
41	10.8	25.1
42	9.1	23.8
43	7.4	22.5
44	5.7	21.2
45	4.0	19.9

TABLE 9 (Frozen Sawdust and Shavings)

Calibration Table for Sensors 1 and 2 (dMean and % M.C.)

dmean	Sensor 1 1" depth %m.c.	Sensor 2 1" depth %m.c.
1	97.5	77.3
2	95.8	76.5
3	94.2	75.7
4	92.5	74.9
5	90.9	74.1
6	89.2	73.2
7	87.6	72.4
8	85.9	71.6
9	84.3	70.8
10	82.6	69.9
11	81.0	69.1
12	79.4	68.3
13	77.7	67.5
14	76.1	66.7
15	74.4	65.8
16	72.8	65.0
17	71.1	64.2
18	69.5	63.4
19	67.8	62.5
20	66.2	61.7
21	64.5	60.9
22	62.9	60.1
23	61.3	59.3
24	59.6	58.4
25	58.0	57.6
26	56.3	56.8
27	54.7	56.0
28	53.0	55.1
29	51.4	54.3
30	49.7	53.5
31	48.1	52.7
32	46.4	51.9
33	44.8	51.0
34	43.2	50.2
35	41.5	49.4
36	39.9	48.6
37	38.2	47.7
38	36.6	46.9
39	34.9	46.1
40	33.3	45.3
41	31.6	44.5
42	30.0	43.6
43	28.3	42.8
44	26.7	42.0
45	25.1	41.2